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THE UNIVERSITY OF ALBERTA

COMPUTER MODELLING OF CONSTANT-THICKNESS FAULT-BEND FOLDS

by

Brian Klappstein

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

IN

GEOLOGY

DEPARTMENT OF GEOLOGY

EDMONTON, ALBERTA

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ABSTRACT

The essential tools in the study of structural geology are geometry and rock mechanics. Hence, many structural processes can be mathematically defined, and modelled by computer-based algorithms. In terrains where most observed phenomena can be predicted by geometric rules of behavior, models can be constructed based on geometry alone.

Thrust-and-fold belts are one terrain type where the application of purely geometric models is appropriate. In such terrains movement is confined for the most part to a vertical plane parallel to the direction of transport where, providing volume is conserved during thrust faulting, area is conserved. Programs developed to date for modelling thrust-and-fold belts have modelled in two dimensions using the principle of area conservation. The programs which model thrust faulting forward in time have not yet addressed the problem of constant-thickness fault-bend folding.

A FORTRAN 77 program is presented which models the formation of constant-thickness fault-bend folding during thrust faulting. The preservation of stratigraphic thickness means this program conserves bed length during thrust faulting, i.e. the internal strain accompanying deformation is accomplished by flexural slip.

In order, the tasks performed by the program to model thrust faulting are: (1) creating an undeformed cross-section of user-specified dimensions, (2) dividing the cross-section

into footwall and hanging wall by a user-specified fault, (3) moving the hanging wall ahead by a user-specified displacement, and (4) displaying the result on a graphics device. The program can create a hanging wall composed of multiple fault blocks by repeating steps (2) and (3).

Moving the hanging wall can be subdivided into substeps which translate and then fold each hanging wall block to conform to the underlying fault at a new location. Most of the program is devoted to a substep of the folding procedure, namely calculation of the orientation of axial planes which preserve thickness in fault-bend folds.

The area balanced models produced by the program can be used to test the validity of interpreted structural cross-sections in two ways: (1) by duplicating in the model the geometry and displacement of each fault in the structural cross-section and comparing the fault-bend folds of each or, (2) by attempting to duplicate the fault-bend folds of the structural cross-section by iterative testing of different faults with the modelling program, and comparing the faults where the folds match. In neither case can differences between the structural cross-section and the model conclusively reject the structural cross-section. However, if the structural cross-section is matched by a model, and if the rules of behavior programmed into the model are valid for the structural cross-section, then the latter is viable.

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INTRODUCTION

The search for answers in the earth sciences has been hampered from the beginning by a lack of observational data. In a field where research is associated with observation, there is often little to observe. Inherent in the subject is the sporadically exposed nature of systems and components under study. Data pertaining to these systems and components are revealed to a greater or lesser extent on erosional bedrock surfaces of irregular relief. In most cases the relief is low relative to the dimensions of the system of interest and what emerges is essentially a two-dimensional picture. The third dimension must be probed by mechanical or geophysical means. In the former case, data retrieved, for example, from a drillhole constitute only a minute sample of the whole; in the latter case, data such as might be retrieved from a seismic survey are compatible with multiple interpretations and often have poor resolution of geologic elements. Because of the incompleteness and imprecision of the resulting three-dimensional databases, the proposition of geological hypotheses demands much interpolation.

Interpolation is just another word for guessing. A "good" guess incorporates and accounts for all pertinent data about a situation, and makes intelligent use of tools such as statistics to enhance the interpretation of the facts. Guesses can be divided into two classes, theimpossible and the possible, with the latter subdivided into the reasonable and

the unreasonable. A tool that helps the geologist decide if a guess is impossible, unreasonable or reasonable is the procedure of modelling.

Not only are modelling techniques valuable in hypothesis testing, but designing a modelling procedure can also provide insight into the processes being modelled. The method, despite limitations arising from the simplification of complex systems into a manageable number of parameters, is most beneficial in areas of geology where conjecture is based on sparse data.

The lack of systematic three-dimensional sampling in geologic environments is particularly inimical to the resolution of geologic structures, and interpretation can be greatly improved by modelling techniques. Before structural theory, which encompasses a wide range of environments and processes, can be incorporated in a modelling procedure, the scope of the project must be delineated. Since no geological model can hope to account for every parameter influencing a system, the problem must be distilled to a manageable number of elements and rules of behavior. A field which has received the attention of modellers, because the behavior is well understood and limited to a narrow spectrum, is the study of fault action in thrust-and-fold belts where all movement occurs along fault and bedding planes. The two guiding principles behind deformation in such regimes are: (1) systems must be balanced (Dahlstrom, 1969), and (2) hanging wall strain accompanying faulting is accomplished by interbed slip.

The procedures developed to date have been limited to simulating the action of three-dimensional components in two dimensions, which requires assumptions about the environment being modelled if the results are to be considered realistic. Most critical to the relevance of the procedure is the assumption that mass transfer in thrust-and-fold belts is confined to the vertical plane parallel to the direction of tectonic transport.

The above criteria are common ground for current modelling routines which are of two types: forward-modelling procedures which simulate the deformation of initially undisturbed strata and subject them to deformation, and reverse-modelling procedures which generate palinspastic restorations from deformed cross sections. The repetitive and accurate manipulation of spatial data required in the simulation of fault geometry mandates a computer-based operation. Examples of forward-modelling computer programs are those developed by Jones (1982) and Charlesworth and Gagnon (1985). The reverse-modelling type is typified in the computer program described by Geiser et. al. (1985).

Both the forward and reverse modelling procedures can be used to test interpretations in structural cross sections. The forward modelling routines are also capable of prediction.

To date, available forward-modelling computer programs do not satisfy the second basic principle referred to above, namely that the strain accompanying thrusting be accomplished by bedding-plane slip. The main purpose of this thesis was to

design and implement a computer-based procedure that models fault-bend fold geometry in accordance with flexural slip. Subsidiary objectives were: (1) to examine current theory and how it is implemented into the computer program, (2) to demonstrate the effectiveness of the procedure by applying it in areas where restored and present-day sections are available, and (3) discuss ancillary research into reverse modelling. The first objective is covered by the first and second chapters of the thesis. The third chapter addresses the second objective, i.e. the demonstration of the modelling procedure. The ancillary research, computer-based palinspastic restoration, constitutes chapter four, which is followed by a concluding discussion of results and future directions in computer-based structural modelling.

THEORETICAL CONSIDERATIONS

A modelling procedure for formulating and testing structural hypotheses requires a rigorous application of the quantitative theory of deformation in the tectonic regime being modelled. However, before the relevant theory can be applied, the scope of the modelling system must be precisely defined. The procedure presented in this thesis is confined to the simulation of two-dimensional geometric interpretations in thrust-and-fold belts where the only folds are fault-bend folds, parallel in style. With the range of geologic structures thus narrowed, the theory to be implemented can be selected.

The theory of deformation of rocks involves the elements of mass, energy and time. Since it is the stated purpose of the modelling procedure to treat only the geometric parameters of deformation, energy factors are not included. The deletion of energy makes the assumption that the geometry can be modelled independently of such parameters as stress. While it is understood that stress is intimately related to the geometry of faults, this factor can be dismissed if we have empirical knowledge of how fault propagation is constrained. This, the cornerstone assumption in the application of theory to this modelling procedure, distills the problem to one involving mass and time only.

From this baseline, a series of assumptions is made that progressively narrows the behavior of the model to a manageable range. These assumptions can be divided into two categories: (1) those determining the configuration of faults accepted by the program and (2) those constraining the internal geometry and shape of the fault-bounded rock blocks involved in deformation.

Faulting style

Assumptions concerning the configuration of thrust faults are derived by observing the geometries of faults particular to the environment of interest. These assumptions constitute generalizations of fault behavior and do not include all rare and special cases. The assumptions are: (1) faults cut up section towards the foreland and, (2) the closer to the foreland of any two faults is the younger, i.e. faults cannot be out of sequence. The first assumption is based on observations of faults in thrust-and-fold belts (Boyer and Elliott, 1982; Bombolakis, 1986). The second assumption is also based on observations that each new fault in a system is generally a splay in the footwall of an older fault (Boyer and Elliott, 1982). Combining these two rules of fault behavior results in the sequence illustrated in Fig. 1.

There are circumstances where these rules of fault behavior are not adhered to. The intercutaneous wedge

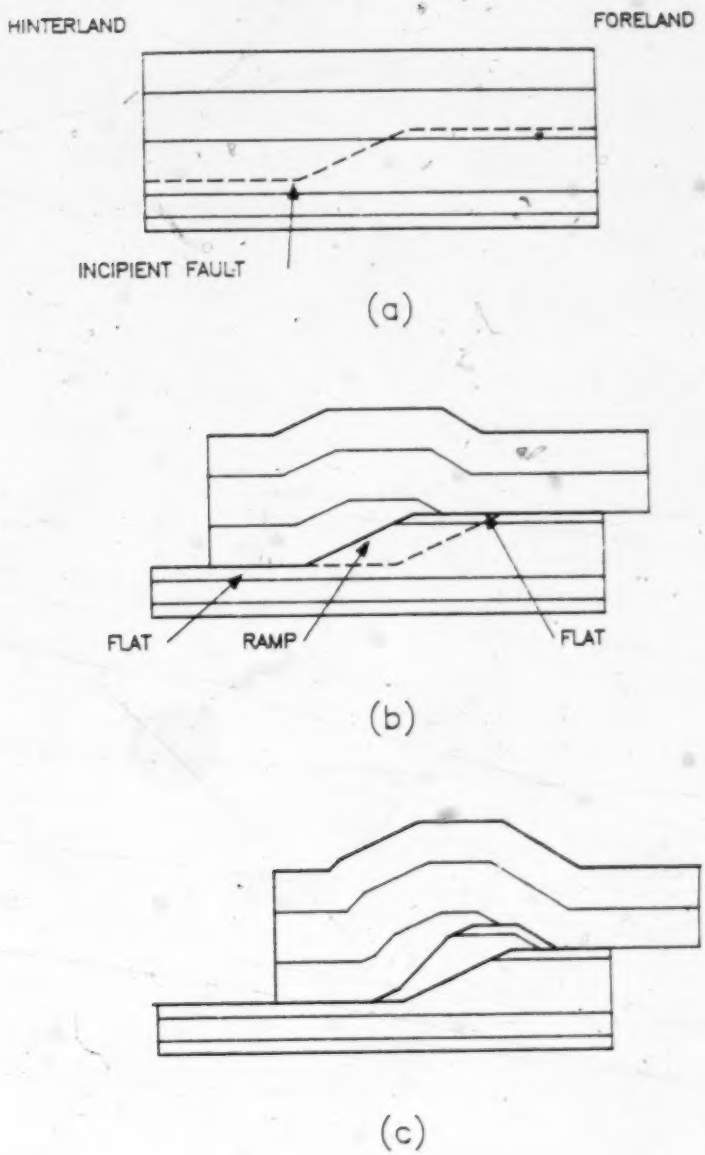


FIGURE 1. A typical two-stage sequence where the ramp of the first fault is replaced by one closer to the foreland. The dashed lines represent incipient faults. (a) Before faulting. (b) After movement along the first fault. (c) After movement along the second fault.

sometimes found at the leading edge of deformation in thrust-and-fold belts is bounded upwards by a fault which cuts downsection from hinterland to foreland until it joins a foreland-verging or upsection fault (Charlesworth and Gagnon, 1985). This fault configuration violates our first assumption, namely that faults cut upsection towards the foreland. A fault configuration which violates the second assumption, namely that fault splays cut the footwall of older faults, is the out-of-sequence fault (Fermor and Price, 1987).

Neither of these conditions can be modelled by the program described in the following chapter. In fact the program cannot model some features compatible with the two stated assumptions. One of these is the fault-propagation fold, which occurs above a blind fault. Though such features are signigicant in thrust-and-fold belts, the additional complexity required to facilitate their simulation was beyond the scope of the thesis.

Geometry of internal deformation

The most important assumption concerning the geometry of internal deformation is that volume is conserved. This implies that modelling should be limited to an environment where no volume loss occurs during thrusting. However, volume loss occurs with faulting in thrust-and-fold belts by such mechanisms as compaction,

pressure solution and metamorphism. Although this loss may be significant in many instances, it was beyond the scope of the thesis project to include such difficult-to-quantify phenomena.

The second most important assumption concerning the geometry of internal deformation states that mass transfer along strike in thrust-and-fold belts is negligible, i.e. there is no lateral movement of material in thrust sheets as they move forward and upward. Lateral transfer of mass occurs in real systems as a result of such features as hanging wall drop faults (Butler, 1982). Although such features result in a loss of cross-sectional area in the hanging wall of a thrust sheet, no attempt is made in this thesis to model cross-sections where area balance is not preserved during deformation. Users of the program should remain aware of this limitation, particularly where the program is being used to test interpretations in environments where the structure is believed to change rapidly along strike, as lateral mass movement is likely.

Combining the assumptions of constant volume and no lateral mass transfer yields the inference that area is conserved in a vertical plane parallel to the direction of tectonic transport. This concept is illustrated in Fig. 2; whereas there is a dramatic change in the geometry of the hanging wall block between Fig. 2a and Fig. 2b., the cross-sectional area remains unchanged. The incorporation of the assumption of constant cross-sectional area limits

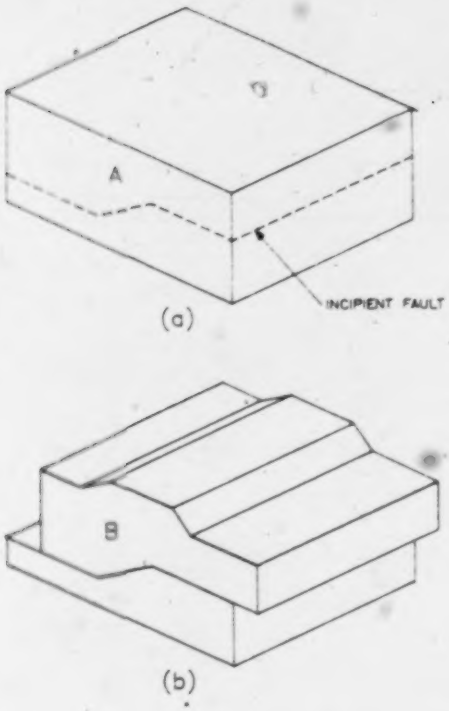


FIGURE 2. Conservation of area during deformation. Area A is equal to area B.

the modelling procedure to simulating compressional tectonics where there is no significant transfer of mass along strike.

Type of strain

Another major assumption made by the procedure is that the internal strain of blocks is accomplished by flexural slip. As an analogy, consider the "folding" of a

telephone book. As the book is folded, strain is accomplished by the pages, representing strata, sliding over one another. Flexural slip causes no change in the true thickness of rock strata as they are deformed. Although this mechanism is dominant in thrust-faulted brittle rocks, it is not the exclusive strain mode (Sanderson, 1982). Simple shear not parallel to bedding and pure shear both result in thickening of beds, a situation that the program cannot simulate. This limits the applications of the modelling procedure, but the alternative, invoking energy parameters to predict where thickening should occur, was unacceptable because of its complication. In general, departures from the flexural slip deformation mode are minor and the deformation associated with thickening of most stratigraphic units is small compared with deformation associated with thrusting and flexural-slip folding.

A corollary of confining hanging wall deformation to flexural slip is that there is no change in the length of individual beds viewed in cross-section as deformation progresses. This is a logical consequence of conservation of area and stratigraphic thickness. The external shape of a rock unit may be changed by interbed slip, for example, a rectangle may become a parallelogram. Another assumption is required to constrain the resulting geometry of the rock units undergoing such strain.

Consider again the analogy of the telephone book.

When the book is folded along an axis parallel to the spine, interleaf slip changes the shape of the open end, but the shape remains square at the spine. If no interleaf slip occurs between the binding and the axial plane of the fold, the pages can be described as being "rigid" at the spine. This concept is applied to the modelling of thrust belts. As strata are subjected to compression, discrete failure planes refract through the layers, commonly in a staircase geometry. Movement of each hanging wall over its irregular fault surface causes folding of the layers by interbed slip. An assumption made during the construction of this modelling procedure is that the individual hanging wall blocks act as if pinned at the hinterland end during displacement (Fig. 3). The decision to pin the hanging wall blocks at the hinterland end specifies the boundary conditions of the model.

If the block behaves as if pinned at the hinterland end, one implication is that there is no vertical variation in the force moving the block. The other implication of pinning the hinterland end of the block is that the foreland end of the block is free to assume any shape resulting from shear during folding. In effect the hanging wall block layers act as if glued together until the block is pushed over a bend in the fault. As illustrated in Fig. 3 only the portion of the block that has been pushed over a bend in the fault is subjected to flexural slip.

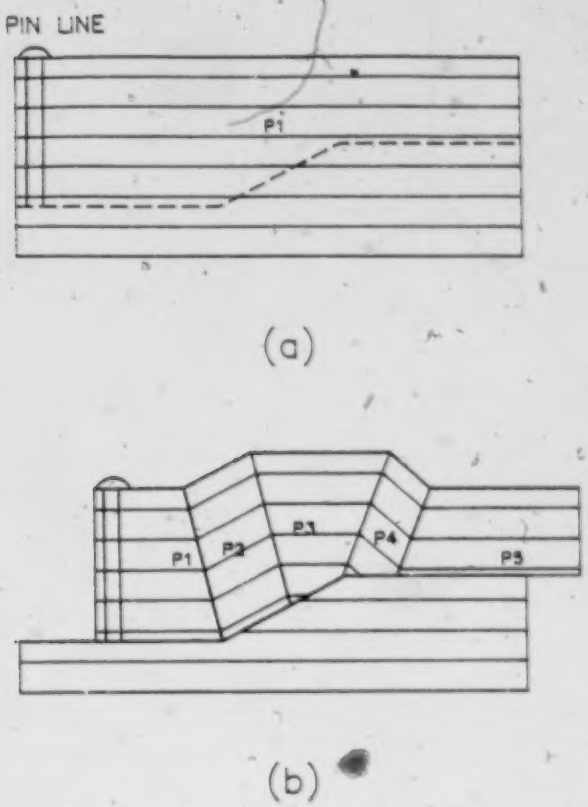


FIGURE 3. Distribution of flexural slip in a thrust sheet with a footwall ramp. (a) Before hanging wall movement. (b) After hanging wall movement. Panels P1 to P5 are referred to in the text.

In reality these boundary conditions do not hold true. Shear is induced within a hanging wall block by external forces during deformation, contradicting the first implication, and the shape changes generated during folding by flexural slip are externally constrained, contradicting the second implication. In certain cases the rule stating that hanging wall blocks are held rigid at the hinterland end must be modified. There are instances, as will be discussed in Chapter 3, that require the pervasive simple shearing of blocks along bedding planes during the

deformation process, thus breaking the pin line. While the validity of the decision to pin blocks at the hinterland, where possible, is questionable in light of the real world behavior, it represents a necessary compromise given the scope of this project.

Fault-bend folding

In the above discussion one consequence of flexural slip on fault-bend folding was not treated, namely the orientation of the axial plane. Because thickness is conserved each axial plane must bisect the interlimb angle of the associated fold (Suppe, 1983).

This makes for a simple solution where the strata of the hanging wall block are parallel to the underlying fault surface (Fig. 3, the axial trace between panels P1 and P2) and the axial plane bisects the bend in the fault. In cases where the strata are not parallel to the underlying fault surface the solution is more complex (Fig. 3, the axial traces between the remaining panels). In such instances the axial plane bisects the interlimb angle but is indirectly and only partially dependent on the underlying fault. The calculation of the orientation of the axial plane in this case is treated in detail in Chapter 3, where the approach is somewhat different from that of Suppe (1983).

This difference in approach is a result of the values desired solved in each case. The equations of Suppe

(1983) were developed to solve for the configuration of a fault knowing the geometry of the fault-bend fold. The purpose of our modelling program, on the other hand, requires an equation to solve for the axial plane of fault-bend folds given the fault geometry and displacement (see Appendix 1 for equation and derivation).

Summary

The assumptions outlined in this section on theory are generalizations and approximations of behavior in thrust-faulted terranes. They do not allow for all possibilities, are not totally accurate in the possibilities they do allow for, and in some cases appear arbitrary. Despite these weaknesses, the rules of geometry that follow from the assumptions provide a foundation for a modelling procedure that produces realistic representations of thrust belts. There is a limit to the complexity of a modelling routine and this forces the designer to make assumptions. Careful consideration of these assumptions can yield a model not unduly hindered by generalization and approximation.

PROGRAM DESCRIPTION

Software and Hardware

In order to implement two-dimensional modelling of fault systems, a computer program was written in FORTRAN 77. Use of this language was restricted as much as possible to the facilities available in all versions of it. As a result, the source code can be compiled with only minor changes by either the Microsoft(R) version 3.00 or Profort(R) version 1.00 Fortran compilers on an IBM-PC or compatible microcomputer. A copy of the source code can be obtained by contacting Dr. H. A. K. Charlesworth, Deptartment of Geology, University of Alberta, Edmonton, T6G 2G1.

All control of the program during execution consists of responses to prompts entered via the keyboard. Alternatively, instructions to the program can be placed in a file of the appropriately sequenced responses which the computer is directed to read in place of the keyboard.

Results are communicated to the user via a graphics device specified by the user at the beginning of a program run. Two different graphics subroutine libraries have been linked with the program. One version of the program uses various Calcomp(R) subroutines from the Host Computer Basic Software library (IBM PC 907 Fortran 77 version), whereas the other version is linked with subroutines from the

PLOT88(R) software package (either the IBM PROF. Fortran or Microsoft Fortran versions). The output device options, which are version dependent, are comprised of the Calcomp 1043 plotter or various kinds of X-Y pen plotters, dot matrix printers and CRTs.

Outline of Algorithm

The algorithm that models the geometry of constant-thickness thrust faulting is embodied in approximately 4500 lines of FORTRAN code. The details of this code need not be known to understand the limitations and applications of the program. Knowledge of the basic tasks performed by the program and of the terminology (Fig. 4) used in the ensuing discussion is all that is needed. Models constructed by the program have the hinterland on the left and the foreland on the right (Fig. 4).

Expressed in rudimentary form, the algorithm consists of four main steps: (1) create a rectangular cross-section representing undeformed strata, (2) divide the cross-section into hanging wall and footwall blocks by the fault trace, (3) displace the hanging wall block along this fault, and (4) display the resulting geometry (Fig. 5). Although the first step is carried out only once in each run of the program, the second and third steps can be repeated any number of times, once for every episode of

deformation. Display of the results, the fourth step, can be performed after any episode of deformation.

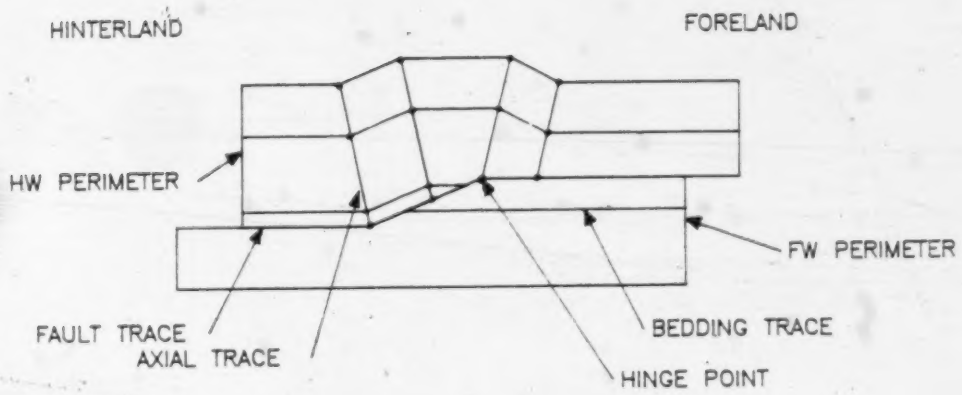


FIGURE 4. Terminology of structural elements. Note that there are four axial traces. Each axial trace has several hinge points of which the lowest is on the trace of the fault.

The complexity of the third step, displacement of the hanging wall along the fault, requires that it be further subdivided into three substeps (Fig. 5). In cases where the hanging wall consists of a single block only the first two substeps are required. Chronologically these are: (3-1) translation of the hanging wall block from its original location to its final destination, and (3-2)

folding of the block to match the shape of the fault at the new location.

If there has been more than one episode of faulting, the hanging wall will consist of two or more fault-bounded blocks which are displaced one by one during step (3). In such cases substeps (3-1), (3-2) and (3-3), redefinition of the current fault trace, must be repeated for each block in the hanging wall, beginning with the lowest. Substep (3-3) is required because the second and each subsequent block to be displaced in this procedure may be folded in substep (3-2) to match a trace consisting partly of the current fault and partly of the perimeter of a previously moved block. Substep (3-3), redefinition of the fault, involves insertion into the fault array of nodes in the upper perimeter of the most recently displaced block in place of the fault nodes beneath the block. Thus, after substep (3-3), the fault trace consists of portions of the current fault and portions of older faults dividing the hanging wall.

Matching a block to the underlying fault trace in substep (3-2) creates a series of folds whose axial traces begin at hinge points along the fault trace. Thus the folding substep (3-2), which implements the core of the theory discussed in the previous chapter, is further subdivided into three repeating steps: (3-2-1) location of a hinge point along the fault trace, (3-2-2) calculation of the axial trace, and (3-2-3) folding of the block along

this axial trace (Fig. 5).

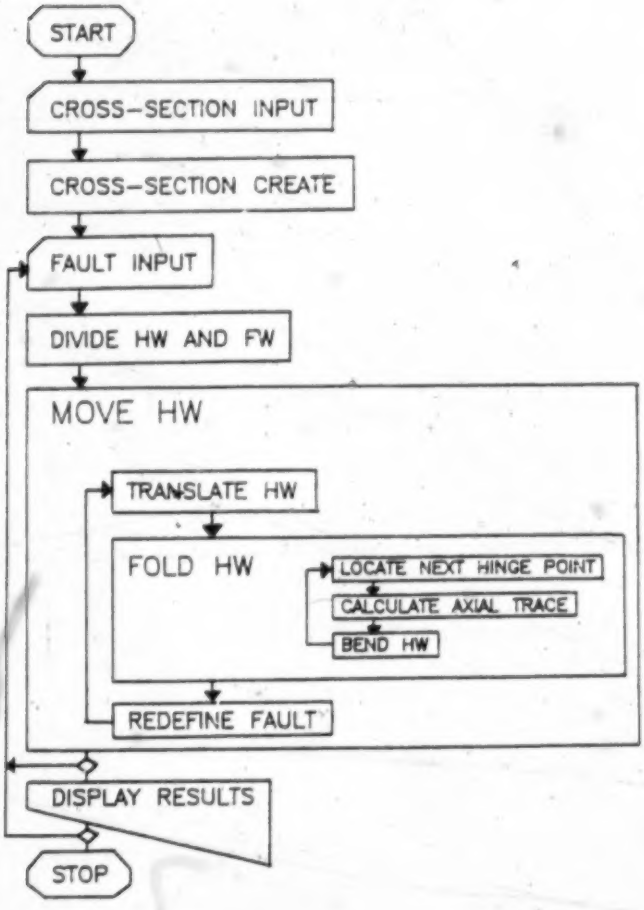


FIGURE 5. Program flowchart.

Parameters specified by the user include the height and length of the undeformed section created in the first

step, and the geometry and displacement of each successive fault. Because the foreland is towards the right end of themodel cross-section the user must specify thrust faults which verge to the right, i.e. propagate up section to the right and move the hanging wall to the right. Other parameters controlled by the user are the thicknesses of stratigraphic units. Since the strata are initialized in a parallel horizontal state the program is limited to modelling situations where no significant changes in regional dip or stratigraphic thickness are apparent in the cross-section.

Only a very minor portion of the computer program is occupied with the graphic display of output. Although the numerical manipulation is valueless without this step, description of the methodology will concentrate on the first three tasks in the algorithm.

Database Organization

Description of how the program executes the three basic steps of creation, division and movement cannot be properly understood without some knowledge of how the cross-section is represented in the computer program. Finding a suitable database structure to store the cross-sections required consideration of the type of data employed by the routine and how these data are retrieved for processing.

Data used by the modelling procedure are real numbers representing two-dimensional cartesian coordinates of nodes defining linear segments. These segments are linked to form traces defining the structural elements manipulated by the modelling program. Each trace can be specified by two vectors, whose elements are the X and Y coordinates of each node in the trace. The traces belong to three families: (1) the stratigraphic contacts, (2) the perimeters of the hanging wall blocks and footwall block and (3) the active fault.

From this basic data format, families (2) and (3) were grouped according to block. This structure assumes a hierarchy where the most important characteristic of a data node is the block to which it belongs. Less important characteristics are the trace to which it belongs and the position in the trace. Thus, once a stratigraphic contact is cut into two segments by a fault trace, the hanging wall segment is processed as part of the hanging wall block and translated, rotated and folded accordingly. The partitioning of the database elements by block membership is in accordance with the way they are retrieved for processing.

To effect this hierarchy, the primary components of the database, namely the stratigraphic contacts, were organized in a three-dimensional array. This array can be thought of as a book, where each page represents a separate block, each row on the page a stratigraphic contact trace

within a block, and each column the number of a node along the trace. Every time the footwall block is cut by a fault some portion of the nodes stored on the page corresponding to the original footwall block must be transferred to a new page. This requires the program to devote a large portion of the run time to database management. A possible alternative to this method, one in which the data were not transferred from page to page, would be to employ pointers. In this method the data belonging to different blocks would be delineated in the primary array by pointers. However, there are problems associated with this method which render it no more efficient. This is due in large part to the variable number of nodes needed to specify each trace. In the initial state, where stratigraphic contacts are straight, only the two nodes marking each end of the segments are needed. As the strata within a block are deformed by bending during hanging wall movement, the length of the stratigraphic contacts stays constant, but the number of nodes per contact grows. The number of nodes also increases each time a stratigraphic trace is cut by a fault. Clearly, the method that leaves the data in one place and employs pointers requires extreme complexity in these pointers to add and delete nodes in stratigraphic contacts and to keep track of the block to which these nodes belong. In the chosen data structure, data must be periodically transferred from page to page but because of this the number of nodes in any one contact remains small

as does the number of memory transfers required to insert nodes. No pointers are required as all data are defined by their position in the array.

The second family of traces which the database must contain consists of the perimeters of hanging wall and footwall blocks. A perimeter trace connects nodes at the ends of stratigraphic contacts. There are several reasons why it is appropriate to store the same data in two arrays. The first reason is to save effort in accessing the data. Although having a second array for perimeter nodes is not memory-efficient, retrieving these nodes in proper sequence from the stratigraphic contact arrays hinders operational efficiency. This hindrance might be acceptable if the perimeter of a block consisted only of the endpoints of stratigraphic contacts and the upper and lower boundaries of the highest and lowest stratigraphic units. However, the modelling program must deal with complications caused by offsets. Offsets occur when a block is cut by a fault that parallels strata for some distance between ramps (Fig. 6). In such cases the program creates additional stratigraphic contacts to define the resulting staircase shape in both the footwall and hanging wall. These additional invisible contacts are never seen by the user as they are not plotted. The stratigraphic contact along which the perimeter is offset must have an extra node which defines where a ramp starts or stops. Because the retrieval of the perimeter nodes from the stratigraphic contact array

requires that the end of every stratigraphic contact be checked for an offset, the process of perimeter retrieval is simpler and faster if the nodes are stored in a separate array.

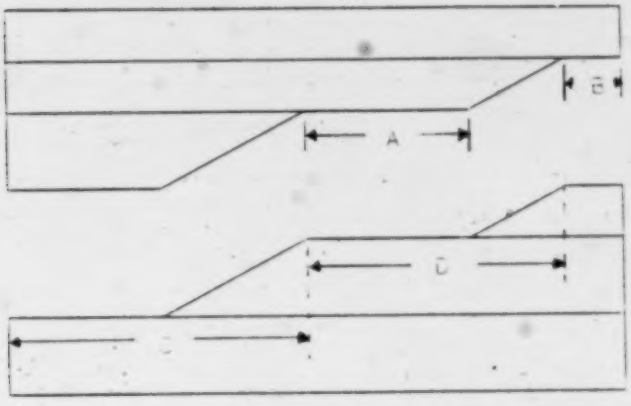


FIGURE 6. The terminology of block perimeters. A and B are the offsets of the second and third contacts in the hanging wall block. C and D are the lateral shifts of the start points in the third and fourth contacts in the footwall block.

Another reason for creating a separate array to store block perimeters is that nodes not coinciding with stratigraphic contacts, invisible or otherwise, may be generated in the perimeter of a block during displacement (Fig. 7, nodes A and B). A node created in this way has no

counterpart in the array that stores the stratigraphic contact nodes and requires the use of a separate array to store the perimeter nodes.

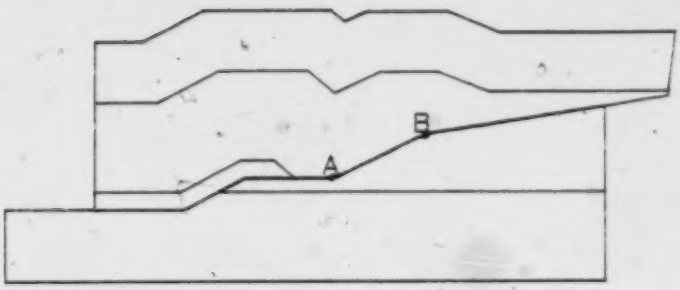


FIGURE 7. Perimeter nodes not coincident with stratigraphic contact nodes. The bends in the perimeter of the hanging wall at points A and B, which occur at bends in the fault, do not coincide with any stratigraphic contact node in the hanging wall.

The philosophy that guided the design of the database structure in the program is that components should be organized naturally, even if more memory is required, because database structures which are more memory-efficient need complicated pointer systems to maintain order.

The primary problem of data storage within the program is that the number of nodes in a trace is the result of a complex interaction of fault shape and displacement. In addition, the number of contacts in a block is unpredictable since invisible contacts are created where faults create irregularities in the shape of the hanging wall and footwall. Arrays must be dimensioned to account for all situations, and since all blocks must be dimensioned to the probable maximum number of stratigraphic contacts in a block and number of nodes in a contact, much memory is left empty.

In summary, the database consists of four basic arrays (Fig. 8). There are two three-dimensional arrays that organize the X and Y coordinates by block, contact and node named BLKX and BLKY, and a pair of two-dimensional arrays, named PERX and PERY, that store the perimeter's X and Y coordinates by block and by counterclockwise node. These basic data arrays are backed up by other arrays that store such parameters as: (1) the spacing (thickness) between stratigraphic contacts, named SPACG, (2) the offset values of the perimeter at the left and right end of each stratigraphic contact, named OFFSPL and OFFSPR, (3) the number of nodes for each stratigraphic contact in each block, named CNLEN, and (4) a multitude of pointer arrays that facilitate retrieval and processing of data.

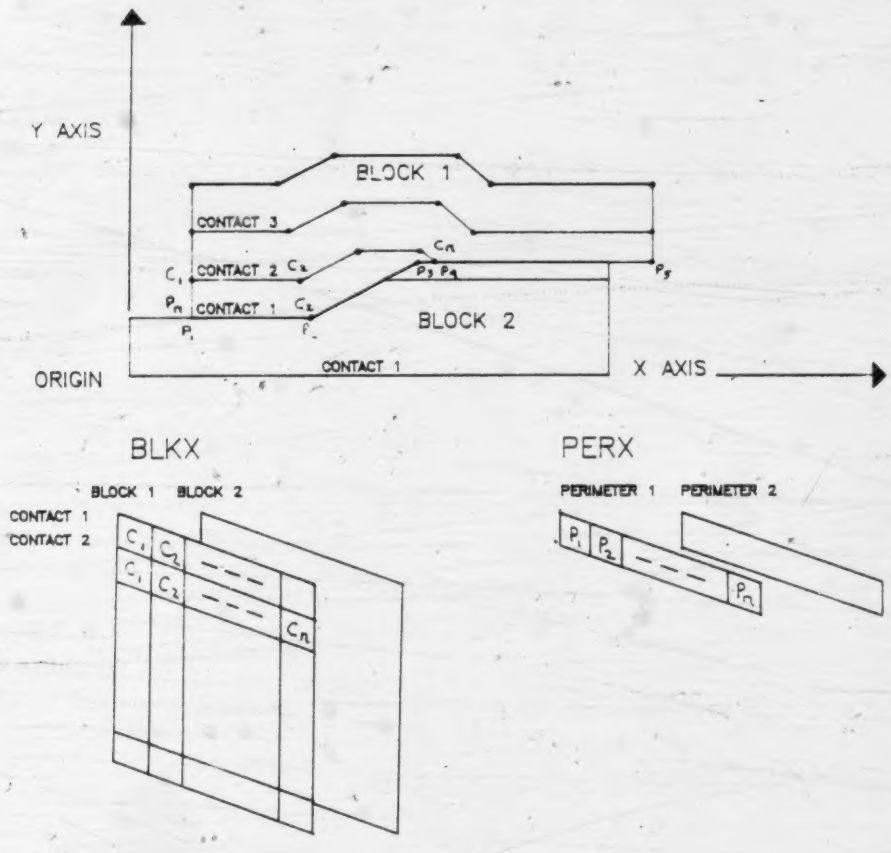


FIGURE 8. Database structure of the computer program. The structure of BLKY and PERY are identical to BLKX and PERX respectively. Only the nodes for contact 2 in block 1 and perimeter 1 are shown.

Creation of the Cross-section

The undeformed section is defined using parameters entered by the user at the keyboard on prompts emitted on the monitor by the program. The supplied parameters set the dimensions of the initial rectangular block and the number

and thicknesses of layers within that block. The numbers that set the length and height of this rectangle are in units which are related to output device units by the relation:

Scale (diagram units/output device units) = F

where F is a user-supplied scale factor. For example, if output device units are centimetres, and the user supplies a scale factor of 10, there will be 10 diagram units to every centimetre in the output plot. Increasing the scale factor shrinks the plot and vice versa. The user should consider the limitations of the output graphic device when choosing the dimensions of the initial cross section and scale factor. For example, if output is directed to a dot matrix line printer for an 8.5" by 11" page, the height of the "deformed" section, accounting for all increases of height due to hanging wall blocks sliding up ramps on the fault, cannot exceed the width of the page. In this case if the height of the original cross-section is less than 5" there is room above the section for fault-bend folds to grow, and room below the section for a title. With such information, and knowledge of the output device units, the user can choose a combination of cross-section dimemsions and scale factor which will generate a plot fitting the page or plotter paper used.

Another series of parameters supplied by the user during the creation step consist of thicknesses, i.e. the spacings between the contacts. BLKX and BLKY are dimensioned to contain 16 stratigraphic contacts but since 8 of these are for the internal use of the program the user can specify the thickness of only 8 stratigraphic layers. The combined thicknesses of the 8 layers should be approximately equal to the height of the initial section. If the user enters 8 thicknesses that add up to less than this height, the program changes the uppermost thickness to make the cumulative thickness match the height. Conversely, the program discards all stratigraphic contacts with a height greater than that of the cross-section and truncates the last layer whose basal contact is below the top of the cross-section.

Once the cross-section has been dimensioned and the layer thicknesses entered, a subroutine is called by the program to generate and store in the appropriate arrays the coordinates of the points at each end of the stratigraphic contacts between layers. The origin of the cartesian coordinate system used to define the positions of all points is located at the lower left-hand corner of the section and all created points are referenced to this origin. The X axis extends horizontally towards the foreland and the Y axis extends vertically. The created X and Y coordinates defining the ends of each stratigraphic contact are stored in one row on the first page of the

three-dimensional arrays BLKX and BLKY. The contacts are stored in inverted order with the lowest in the first row and the highest in the last row.

At this stage several ancillary arrays are initialized. These include the array containing the lateral shift between the start points of successive stratigraphic contact traces (Fig. 6), named SHEAR, and a number of pointer arrays indicating which nodes in the contact traces belong to which perimeter nodes and vice versa, named CPERL, CPERR and PERC.

Footwall Division

Once the database arrays contain the initial undeformed cross section, the program repeats the second and third main steps of the program, the number of repetitions being equal to the number of deformational stages requested by the user. The second step, division of the cross-section by the fault into hanging wall and footwall blocks, can be separated into three substeps: (2-1) defining the fault, (2-2) locating the entry and exit points of the fault in the footwall, and (2-3) reorganizing the database to accommodate another block.

The first of these substeps, specifying the fault geometry, begins with communication between computer and user. The fault geometry, generally a series of flats and ramps, is entered at the keyboard in response to prompts by

the program. The program stores the fault in a pair of one-dimensional arrays, named FX and FY, that contain the X and Y coordinates of the nodes defining a series of linear segments. These are entered by the user, with all X values entered first. However, because the user may find it difficult to visualize the coordinates needed to define a desired geometry, the values entered may consist of the horizontal lengths and dips towards the foreland of the segments. The user also specifies the height at which the fault cuts the left-hand edge of the cross-section. The program converts these values into the cartesian coordinates of the fault nodes. If the fault extends beyond the cross-section dimensions the program truncates it and creates a node where it intersects the edge of the cross-section. Should the user create a fault that ends inside the cross-section, an error message is generated and the user is requested to re-enter the values.

Once the fault has been defined, the cross-section must be separated into hanging wall and footwall blocks. To accomplish this function the program uses a search point or cursor which it moves along the fault. The cursor is used to find the locations along the fault where it enters and exits the footwall. This substep is unnecessary for the first stage of deformation as the entry and exit points on the footwall coincide with the first and last nodes of the fault. However, where is more than one stage of deformation, younger faults may start by following an older

fault, depart from this fault to enter the footwall at some point along the older fault, and rejoin the older fault before it exits the cross-section. In such instances horses or blocks entirely bounded by faults are created. Multiple horses can be created in a single stage if the fault enters the footwall and rejoins an older fault more than once. By scanning the cursor along the fault trace the program can determine which sections of the fault coincide with older faults and which sections cut the footwall. As long as the search loop does not find the cursor position inside the footwall, the cursor is incremented a short distance along the fault and retested. When the cursor is found inside the footwall, the entrance and exit points are located on the footwall perimeter, the footwall is divided, and the cursor position is set to the exit location. The routine terminates when the cursor position equals the last fault node. The program displays an error message and requests re-entry of the fault geometry if the user creates a fault, in multiple fault stage models, that cuts any block but the footwall block. If the fault is discovered to cut down section in the footwall another error message is displayed along with the request for re-entry of the fault.

The third substep of the footwall division routine, rearranges the database to accommodate the new hanging wall block or blocks. Specifically, division is accomplished by first finding the intersections between the new fault and the stratigraphic contacts within the footwall, which

always occupies the last used page in the BLKX and BLKY arrays, and then transferring the footwall portions of these traces to rows on the next empty page of BLKX and BLKY. For example, after two fault stages there would be two hanging wall blocks stored on pages 1 and 2 of BLKX and BLKY; the footwall would be stored on page 3. After the division step of a third fault stage, the new smaller footwall would be stored on page 4 with the new hanging wall block remaining on page 3. If the new fault has created two new hanging wall blocks at once the process is repeated and the footwall traces are transferred again to the next empty page, leaving the hanging wall on the former footwall page. Following the transfers necessary to accommodate the new hanging wall block or blocks, new coordinates are placed in the perimeter arrays, PERX and PERY, and the associated pointer arrays reset.

This description oversimplifies the manipulations involved in the transfer of points to a new block and the reorganization of those left in the old block. There are many ways a fault can divide a block depending on the lengths and dips of its linear segments. Not all allowed combinations make geologic sense and it is up to the user to configure faults correctly.

It is important to know that the program makes invisible alterations to the database when separating the cross-section into two blocks with a fault. The alterations, briefly described earlier, involve the

addition of unseen traces parallel to bedding, unseen because although the traces exist in the database, they are not original stratigraphic contacts and are not drawn by the plotting routines. These stratigraphic traces, for the internal use of the program, can number up to 8 and are inserted into hanging wall and footwall blocks at hinge points in the new fault. It is because the external shape of a block is defined by segments connecting the ends of stratigraphic contacts, that invisible contacts must be inserted into the new hanging wall and footwall blocks where the fault trace folds. Such contact traces define the resulting irregular shapes in hanging wall and footwall blocks at a fault fold and how such shapes change when a block is deformed by folding and interbed slip.

Hanging Wall Movement

The final major step, after the creation of the initial cross-section and its division into blocks by the fault, is the movement of the hanging wall block by the displacement specified for that fault. The program to this point has dealt with a minimum of structural geology, being primarily occupied with database creation and management. It is during the third step that most of the theory discussed in the previous chapter is applied. The theory is embodied in two rules which form the basis of the algorithm used by the computer to simulate the movement of a block

composed of stratified rock along an irregular fault surface.

Preservation of the thickness and length of individual layers is the first and foremost of these rules. This rule can be restated as: the strain accompanying the internal deformation of blocks is accomplished by flexural slip. Another important and obvious rule is that any block displaced along a fault must conform to the fault in a way that leaves no empty space. These two rules form the basis of the method implemented to accomplish hanging wall movement.

With these rules, thrust faults can be modelled by a procedure which disregards the portions of the fault traversed by the hanging wall during displacement. If the lengths and thicknesses of layers are not changed during deformation then it is irrelevant what folding the hanging wall block had to undergo as it was displaced along the fault. To model hanging wall movement an undeformed hanging wall block can therefore be translated intact to the destination point on the fault and folded to conform to the shape of the fault. The situation is more complicated in multiple-stage fault models where hanging wall blocks may have been folded by older fault displacements. Since all older bends in a block are undone by movement, the block must be straightened before being refolded to mate with thefault at the destination. The straightening process destroys all old bend points in the contact traces,

preserving the length, spacing and relative lateral shift of successive traces when it defines the new trace endpoints. Straightening reduces to a minimum the data necessary to define the block.

Since the final position of the hanging wall block determines its shape, the algorithm simulating fault movement can be described in terms of the following substeps: (1) determination of the point on the fault where the hinterland end of the hanging wall block will be after displacement, (2) unfolding of the hanging wall block to its original straight formation contact shape (if necessary), (3) translation of the straightened block to the position where the hinterland endpoint equals the point on the fault found in substep (1), (4) rotation of the block so that its base overlies the fault segment at this position, and (5) folding the block from hinterland to foreland until it perfectly matches the fault (Fig. 9). In implementing this algorithm, conceptual substeps (2), (3) and (4) are combined by replacing old coordinates in the hanging wall block nodes with the coordinates of the new straight, translated and rotated hanging wall block. In multistage models, where the hanging wall block has been folded in an earlier event, straightening deletes the extra nodes needed to define crooked contact traces from the database. The last substep of this algorithm, the folding of a block to the fault surface, constitutes the majority of the code dedicated to the movement of hanging wall

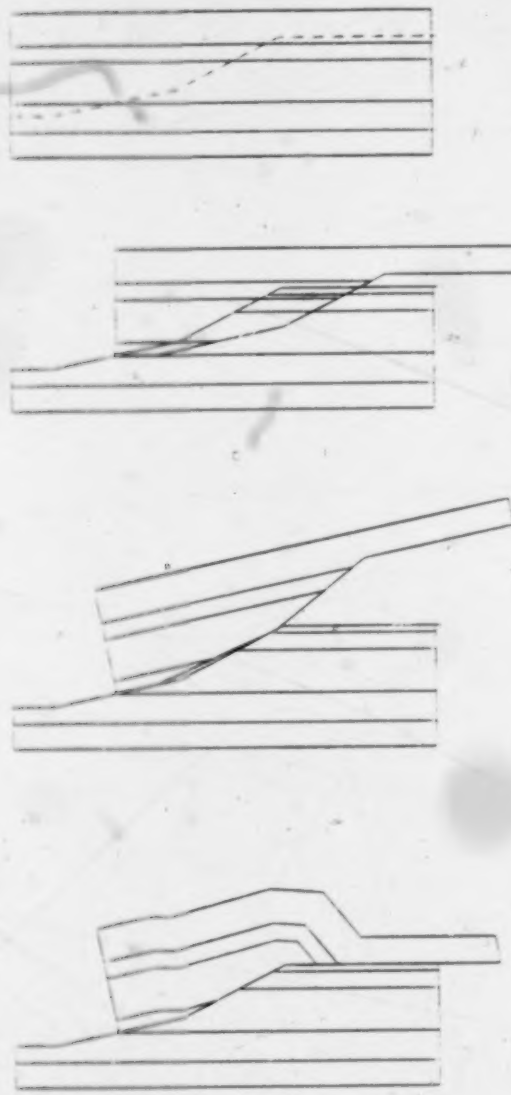


FIGURE 9. Translation, rotation and folding of the hanging wall. (a) The incipient fault. (b) Translation of the hanging wall. (c) Rotation of the hanging wall so that it becomes parallel to the fault at the destination point. (d) Folding of the hanging wall to conform to the fault.

blocks.

The Folding Routine

The folding routine is the heart of the program. For each deformational episode, it consists of a repeating sequence of four substeps: (1) locate the next hinge point on the fault trace, (2) calculate the slope of the axial trace passing through this point, (3) determine whether the axial trace intersects previous axial traces and where this occurs calculate the resulting axial trace, and (4) bend the stratigraphic contacts and the perimeter of the hanging wall up (for synclines) or down (for anticlines) along this axial trace. This series of substeps is repeated at hinge points along the base of the hanging wall block from left to right until the right-hand tip of the hanging wall block is lying along the fault.

Substep (1) hinge point location

The hinge point for any fold in the hanging wall must occur at either a bend in the fault or a bend in the hanging wall. At a hinge point the base of the hanging wall block departs from the fault trace forming either a gap between the block base and fault, or an overlap (Fig. 10).

Pointers, which are incremented following each fold, identify the first fault node and the first hanging wall

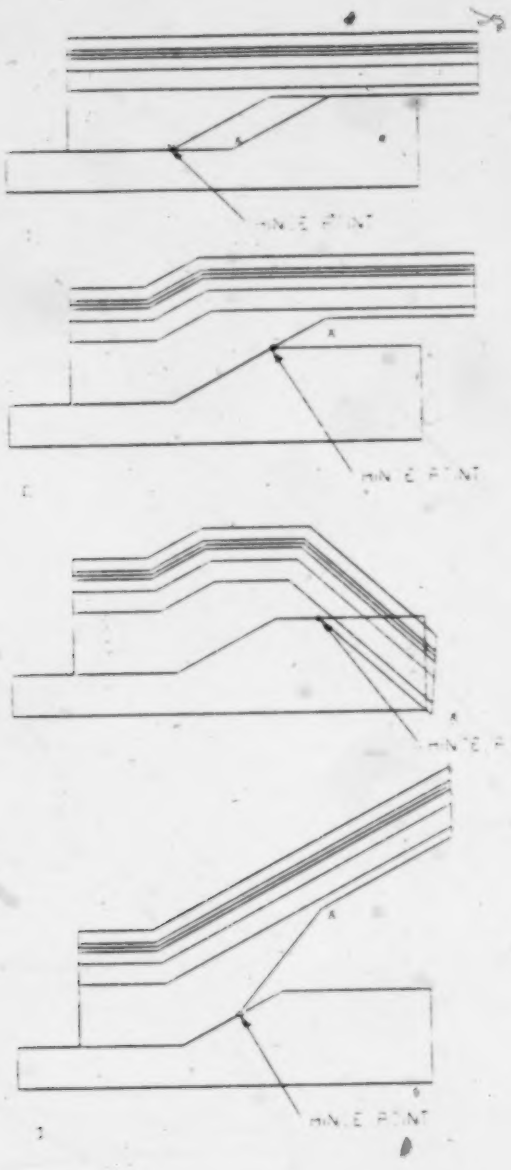


FIGURE 10. The four types of hinge points on fault traces. (a) Hinge point at fault bend, overlap. (b) Hinge point at fault bend, gap. (c) Hinge point at perimeter bend, overlap. (d) Hinge point at perimeter bend, gap. In all cases X marks the first node on the base of the hanging wall block not on the current fault segment.

node to the right of the last hinge point. The search for the next hinge point uses these pointers to find the first node on the base of the hanging wall block to lie off the fault. Whether this node is off or on line with the current fault segment is then determined. If the node is on line, the next hinge point coincides with the fault node at the right-hand end of the current fault segment (Fig. 10a,b). If the node is off line, the next hinge point coincides with the last node at the base of the hanging wall block that is on the current fault segment (Fig. 10c,d). If the hanging wall overlaps the fault, the fold is a syncline (Fig 10a,c); if there is a gap between the two, the fold is an anticline (Fig. 10b,d). A deformational episode involving four sequences of the four substeps (including locating the hinge points) is shown in Fig. 11.

Substep 2, calculating axial traces

Where bedding parallels the fault, finding the slope of the axial trace is trivial. In all other cases, the following two parameters, measured at each hinge point, are required to calculate the slope of an axial plane (Fig. 12):

Gamma - the angle before folding between the fault to the right of the hinge point and the normal to bedding measured clockwise from the normal to

bedding, and

Tau - the angle before folding between bedding and the perimeter of the hanging wall block right of the hinge point known as the truncation angle.

Other parameters in determining the slope of the axial trace are :

Theta - the angle between the normal to bedding and a "test" axial plane, measured clockwise from the bedding normal,

Alpha - the angle between a test axial plane and bedding to the left, and

Beta - the angle between a test axial plane and bedding to the right.

For anticlinal folds (Fig. 12a), for a given value of Theta,

$\alpha = 90 - \Theta$, and

$\beta = \pi + \Theta - \gamma - \text{Arcsin}(\text{Sin}(\gamma - \Theta)/(\text{Cos}\Theta/\text{Tan}\tau - \text{Sin}\Theta))$.

If the fold is synclinal (Fig. 12b), the equation is the same for α, but for a given value of Theta,

$\beta = \Theta + \gamma + \text{Arcsin}(\text{Sin}(\gamma + \Theta)/(\text{Cos}\Theta/\text{Tan}\tau + \text{Sin}\Theta))$.

These equations, whose derivation are shown in Appendix 1, hold for all types of anticlinal and synclinal folds regardless of whether the hinge point is a bend in the base of the block or a bend in the fault.

The desired value of Θ is that where $\alpha = \beta$, a relationship demanded by the necessity that thickness

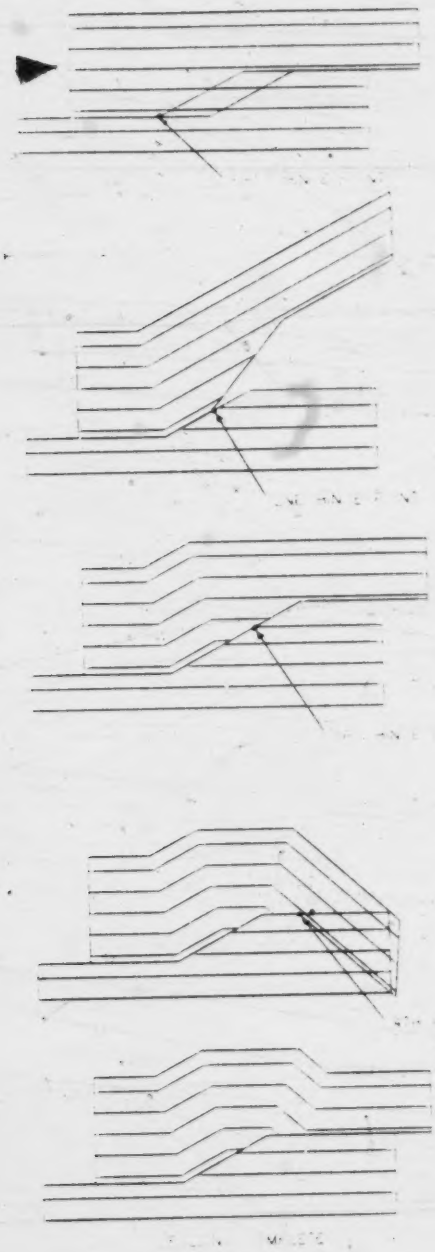


FIGURE 11. Step-by-step folding of the hanging wall.

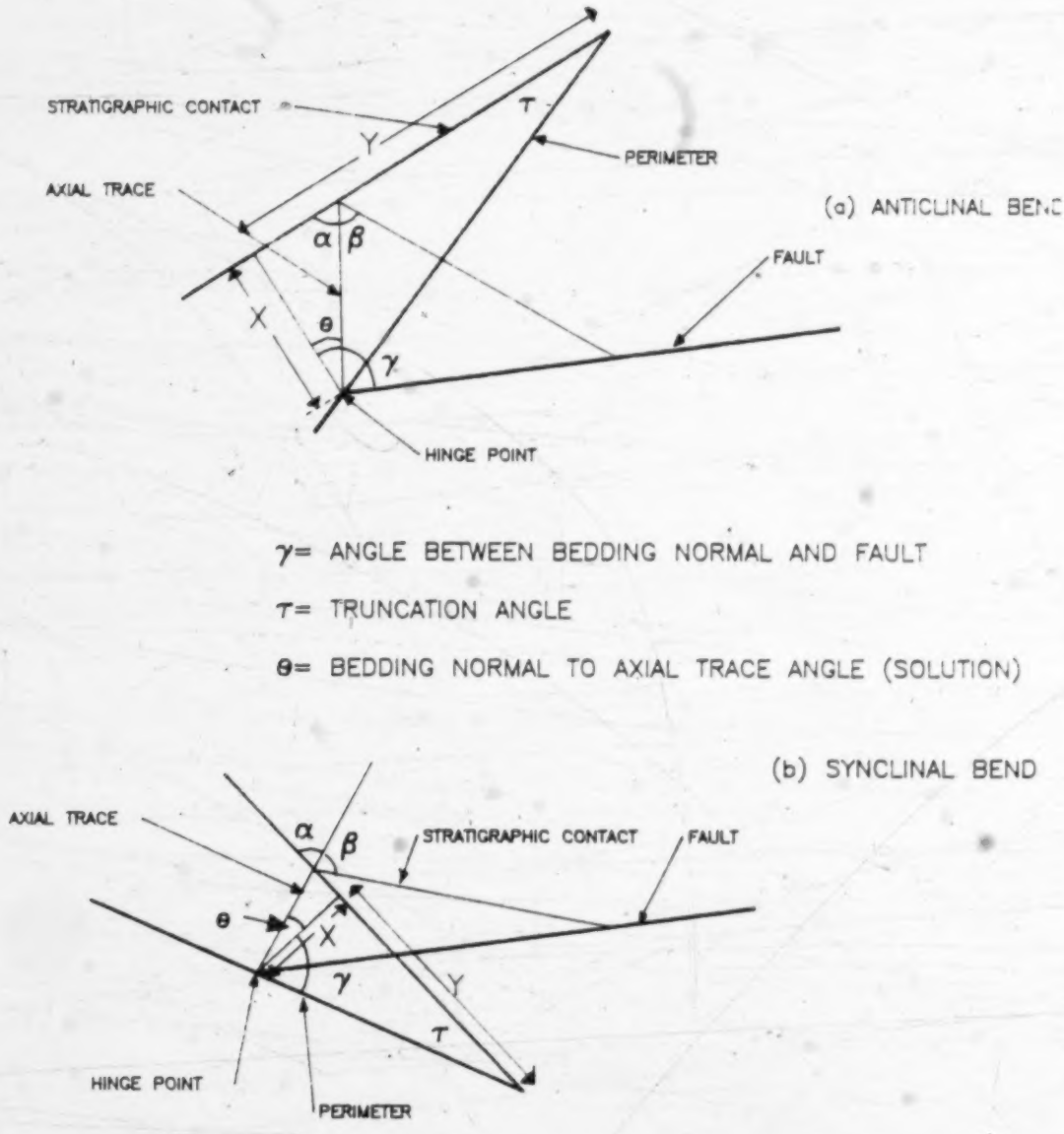


FIGURE 12. The geometric elements used in calculating the axial traces of fault-bend folds shown for both anticlines (a) and synclines (b).

remain constant across the axial trace. The procedure for finding the slope of the axial trace is thus an iterative search for $\alpha = \beta$.

In this search, beginning with $\theta = 45$ degrees, successive values are incremented or decremented from the previous value by a search angle whose magnitude, beginning with 22.5 degrees, is halved on every pass through the loop. The result determines whether the correct value for θ is less than or greater than the current test value of theta. The search terminates either when the absolute value of $\alpha - \beta$ is less than .05 degrees (an acceptable solution is found, shown in Fig. 13) or the search angle is less than .005 degrees (there is no solution, shown in Fig. 14).

The problem of no solution can be thought of as not having enough length in the contact trace, relative to its height above the inflection node, to enable it to be bent to the fault surface while maintaining layer thickness. In other words bedding is truncated at too great an angle, i.e. the angle τ is too great. As Fig. 14 shows, the two functions graphing α and β versus θ converge on one another but never meet for any value of θ. The decision routine, which controls the direction the iterative search proceeds in, would in this case narrow in on the "best" value of θ, i.e. where the functions of α and β are the closest. This value of θ however, does not conserve thickness in the folded layer. The solution to this problem

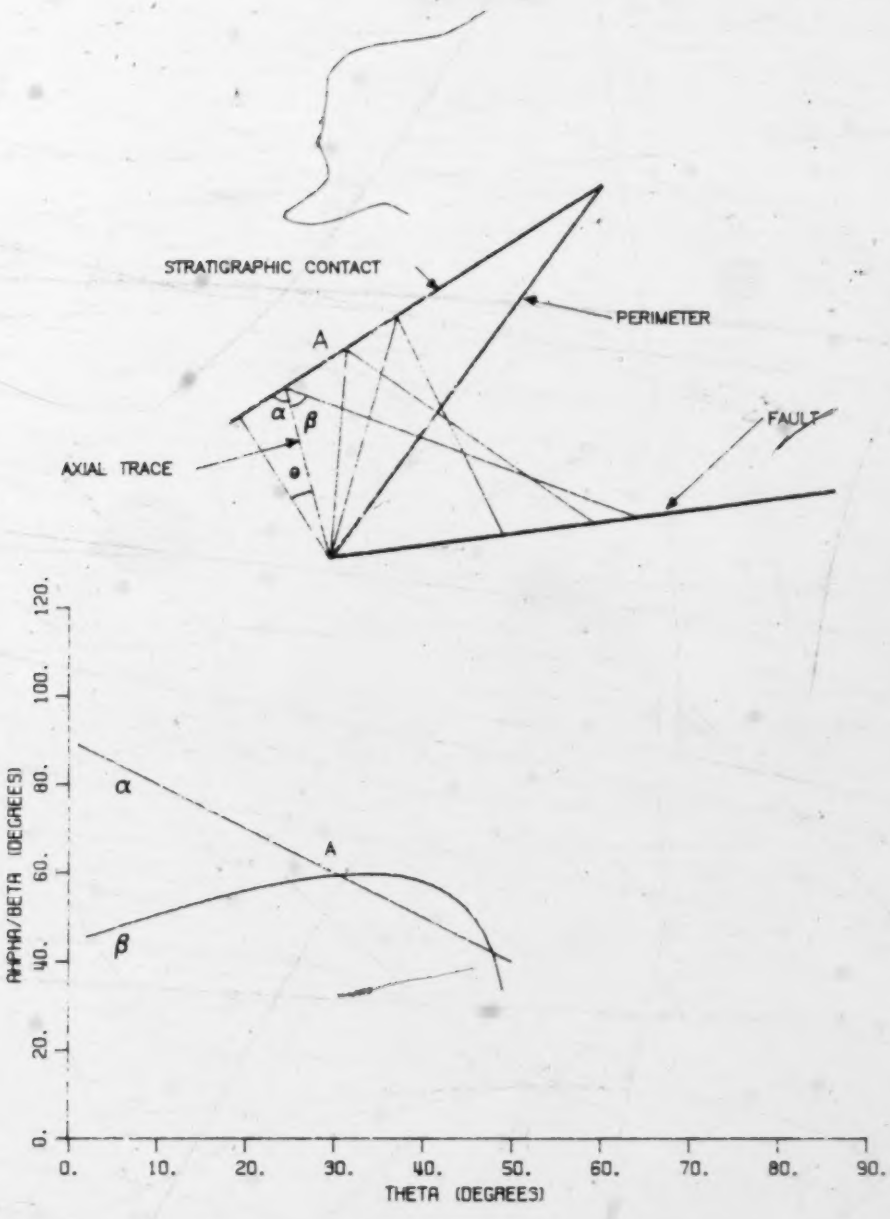


FIGURE 13. The geometry of the fault, bedding and perimeter for a number of cases where the bedding trace is folded to contact the fault. Only at A does the axial trace preserve stratigraphic thickness (=). The accompanying graph shows the functions of alpha and beta versus theta and the point at which the axial trace preserves thickness.

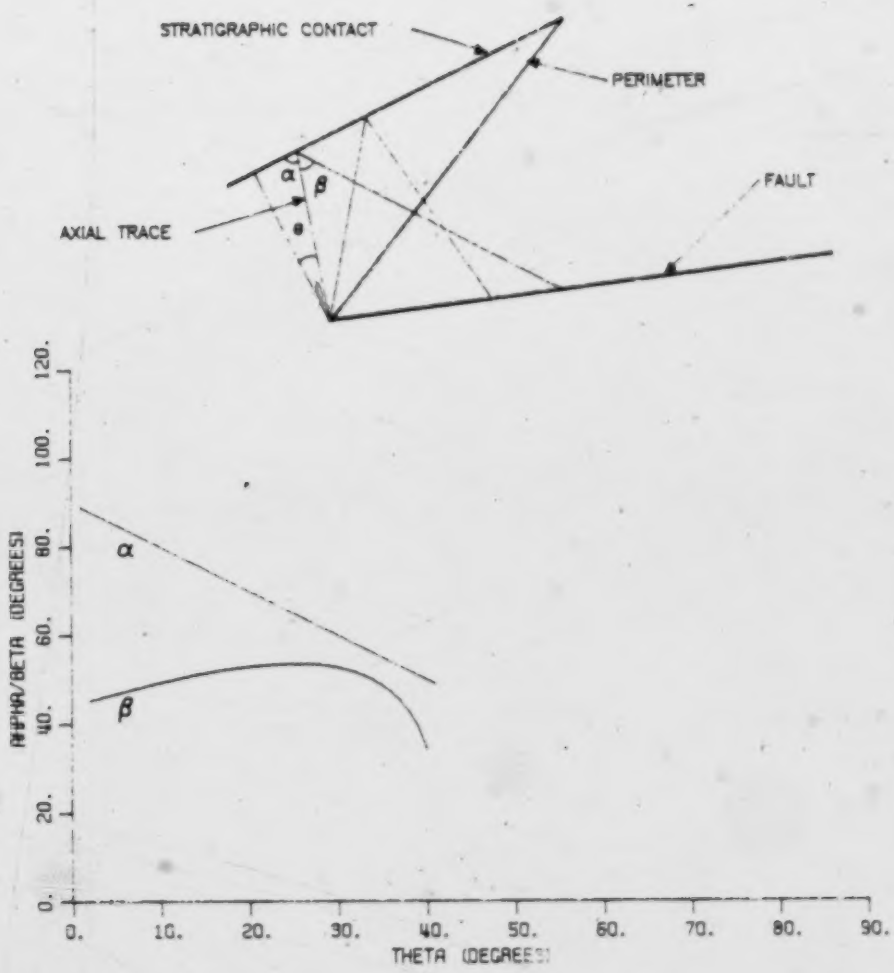


FIGURE 14. A situation where the geometry of the fault, bedding and perimeter are such that there can be no axial trace which satisfies the condition that alpha equals beta.

is to decrease the truncation angle such that an axial trace can be found. The program decreases this angle, while preserving area in the hanging wall, by imparting bed-parallel simple shear to the strata between the hinge point and the first stratigraphic contact above the hinge point (Fig. 15). In such cases the original pin line at the hinterland end of the hanging wall block is broken.

Complicating the determination of an axial trace is the existence of what has been called the second mode axial surface (Suppe 1983). For all folds there are two axial traces that satisfy the equality of angles stipulation (Fig. 16). The first mode fold always has a greater apical angle than the second mode fold. The search routine will find the first mode axial trace because of the angle at which θ is initialized for the binary search.

The test for equality between α and β initializes this angle to 45 degrees and searches lower if α is less than β and in the direction of β closing on α if the reverse is true. Consider the α and β versus θ plot for both the first and second mode fault-bend folds (Fig 16). Note that the α and β functions intersect twice and that α is less than β for a range of θ values. For most second mode axial surfaces, the α/β angle is less than 50 degrees, and θ is therefore greater than 40 degrees. Given the above criteria for start angle and search direction, and the relation between the α and β functions at the second mode axial surface, one can see

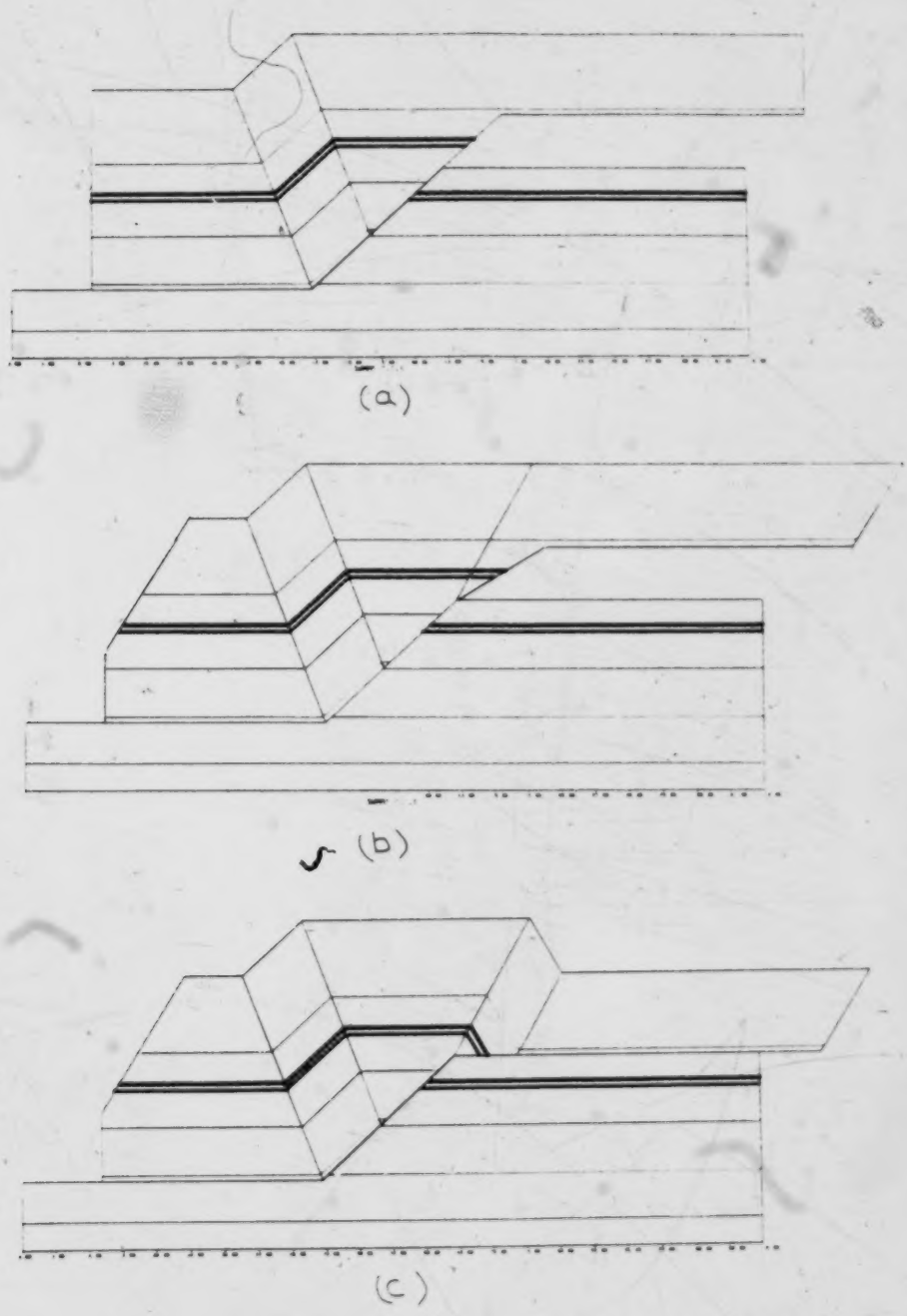


FIGURE 15. The imparting of a bed-parallel shear to a hanging wall block to allow the folding at a hinge point where the cutoff angle is too steep otherwise. (a) The hinge point for which there is not a conventional axial trace solution. (b) After the global shearing. (c) completion of the fold.

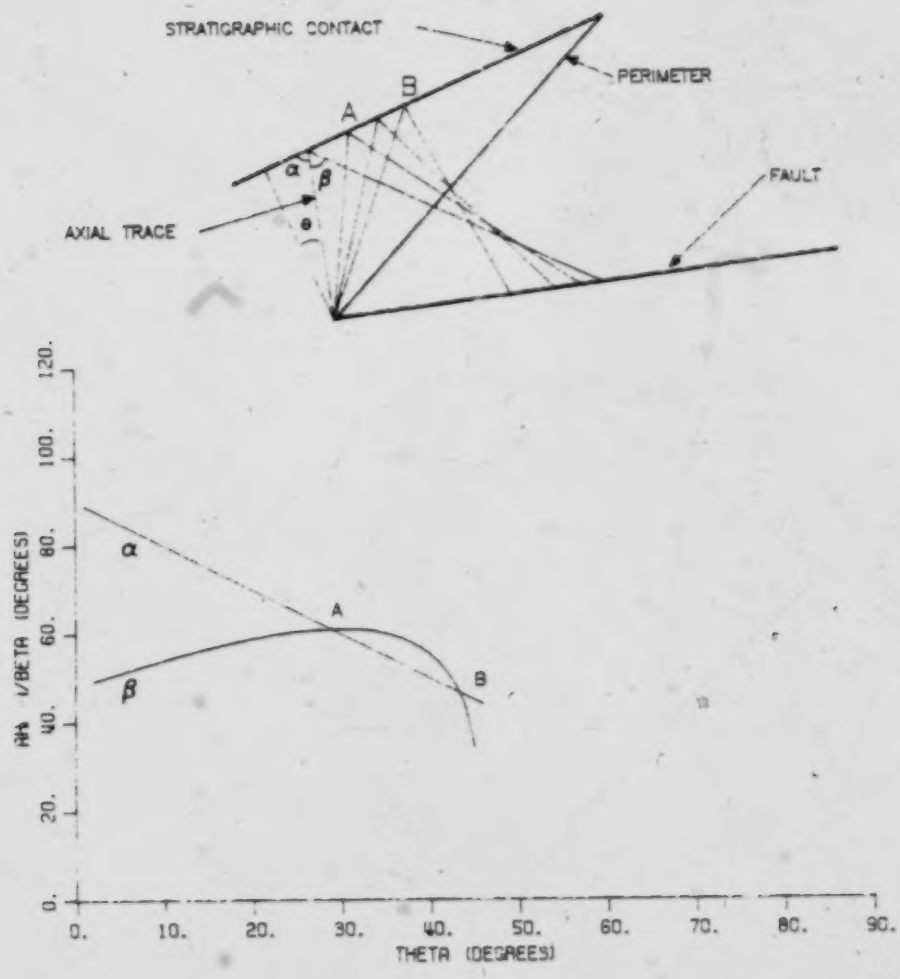
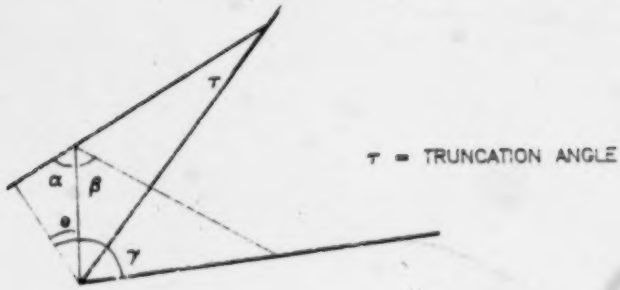


FIGURE 16. The geometry of the second mode axial surface (the axial trace B). Thickness is preserved by both axial traces A and B.

that the routine will recover the first mode axial surface in any reasonably expected situation.

Only under extreme circumstances will the angle between the bedding normal and the fault be less than 40 degrees or greater than 160 degrees: angles less than 40 degrees imply synclinal folds in the fault with apical angles of less than 130 degrees and greater than 160 degrees imply anticlinal folds in the fault with apical angles of less 110 degrees, i.e. ramp angles for single stage faults of 50 degrees to 70 degrees. For the low end of this spectrum (δ = 40 degrees) there is a solution for any values of τ up to about 53 degrees (Fig. 17). As shown by Fig. 16 all solutions for δ = 40 degrees below a truncation angle of 50 degrees are synclinal folds. For a δ value of 160 degrees there is only a solution for hanging wall blocks where the value of τ is less than about 10 degrees (Fig. 17). The inference to be gained from the above relationship is that while tight synclinal folds in the fault can be accommodated by almost any shape of hanging wall during the folding sequence, tight anticlinal folds in the fault require the hanging wall above to have very small truncation angles. Figure 17 also demonstrates that where, as is commonly the case, bedding is almost parallel to the fault ahead an anticlinal hinge point prior to a fold (δ equals 90 degrees), the truncation angle of the hanging wall block cannot become much steeper than 30 degrees if the block is to be folded in a constant



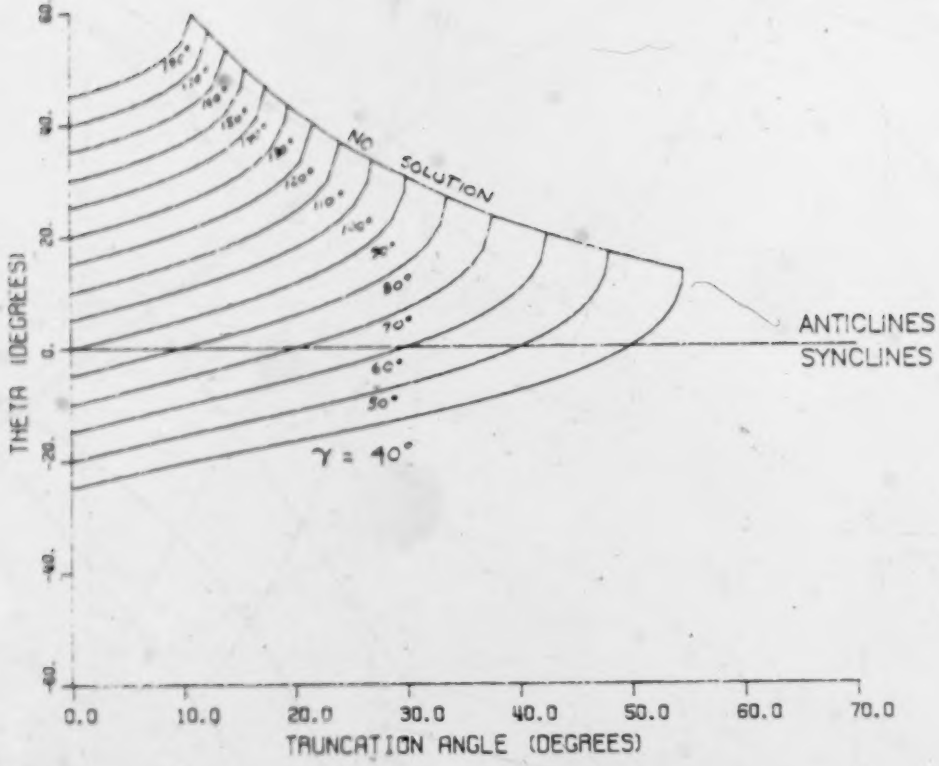


FIGURE 17. The relationship between the truncation angle ( ) and the angle between the perpendicular to bedding and the thickness-preserving axial trace ( ) for various angles of Gamma. The range of gamma values between 40 degrees and 160 degrees encompasses the reasonably expected configurations between fault and bedding.

thickness mode. This angle of 30 degrees is therefore a practical limit for the dip of ramps on the user-specified faults.

Substep (3) Calculating coalescing Axial Traces

For each fold in the hanging wall, each stratigraphic contact above the fault is bent at the point where it intersects the axial trace. It is bent up or down to the new stratigraphic dip, calculated in substep (2), which preserves layer thickness and folds the base of the hanging wall to the fault. The intersections between the axial trace and the stratigraphic contacts, i.e. the hinge points for each contact, are in many cases simply the solution of two linear equations, one for the unbent segment of the stratigraphic contact, and one for the axial trace. If this was always the case substep (3), the calculation of coalesced axial traces, would not be required.

However, consider the situation where the current axial trace intersects the axial trace of the previous fold (Fig. 18). Where two axial traces converge upward and intersect within the hanging wall they must be replaced by a single axial trace which is not parallel to either of the converging traces below. To preserve layer thickness, the slope of this resultant trace must be such that it bisects the angle formed by the strata on the left-hand side of the

previous axial trace and the newly calculated dip of the strata on the right-hand side of the current axial trace. In such cases the axial trace which the strata must be folded about consists not of a line, but of two non-parallel segments. Thus, before the program can proceed to fold the hanging wall block after the axial trace calculation, it must determine whether the current axial trace intersects the previous axial trace.

There are many situations where this is likely to occur, e.g. where there are two consecutive synclinal bends in the fault (Fig. 18), or where a tight synclinal bend is followed by an open anticline bend (Fig. 19). In such instances the separation between fault nodes and the interlimb angle of the synclinal bend are critical.

Substep (3) does not end when an intersection between the current axial trace and the previous axial trace is found and the resultant axial trace calculated. Before the program can proceed it must check to see if the resultant trace intersects the next previous axial trace. If it finds an intersection (within the hanging wall boundary), it must calculate a second resultant axial trace and check for yet another intersection. This continues until either the calculated resultant trace does not intersect any previous axial trace within the hanging wall boundary or there are no previous axial traces to check. The structure that results when two or more axial traces intersect is an inverted tree whose branches point

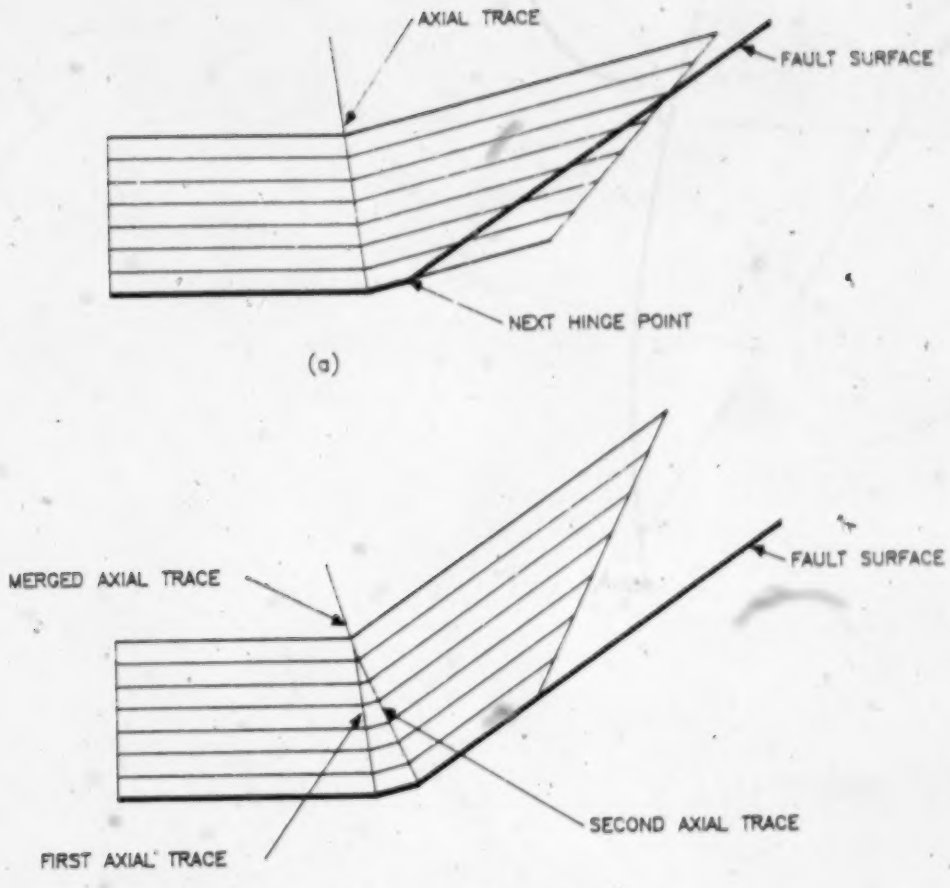


FIGURE 18. The merging, during the folding of a hanging wall block, of two consecutive axial traces.

down. This is a binary tree, binary because each branch of the tree can only have two branches at any node of intersection. During folding, it is theoretically possible for an axial trace to intersect exactly a node formed by a

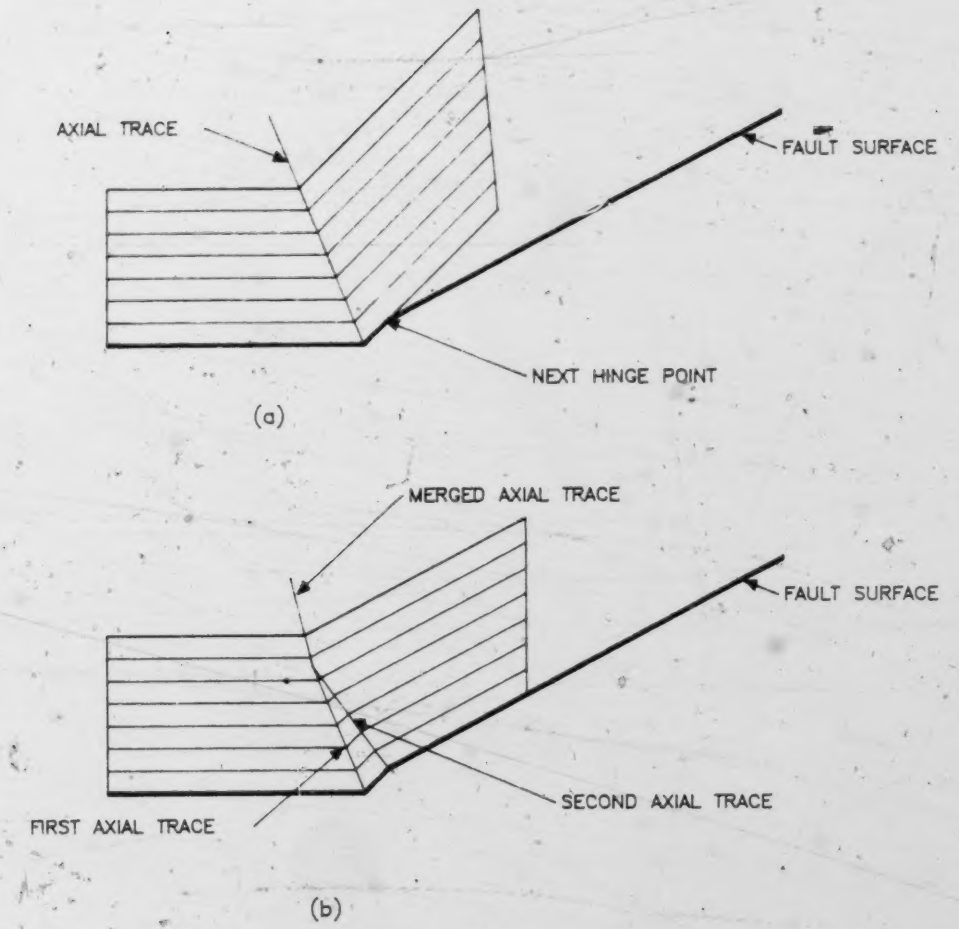


FIGURE 19. The merging of two axial traces during the folding process. Note the second axial trace originates at an anticlinal fault bend.

previous intersection, making a three branch node, however the floating point mathematics used by the computer make this possibility extremely remote. Complex trees can result where the fault geometry and hanging wall block shape combine to produce a number of close-spaced hinge points with non-parallel axial traces (Fig. 20).

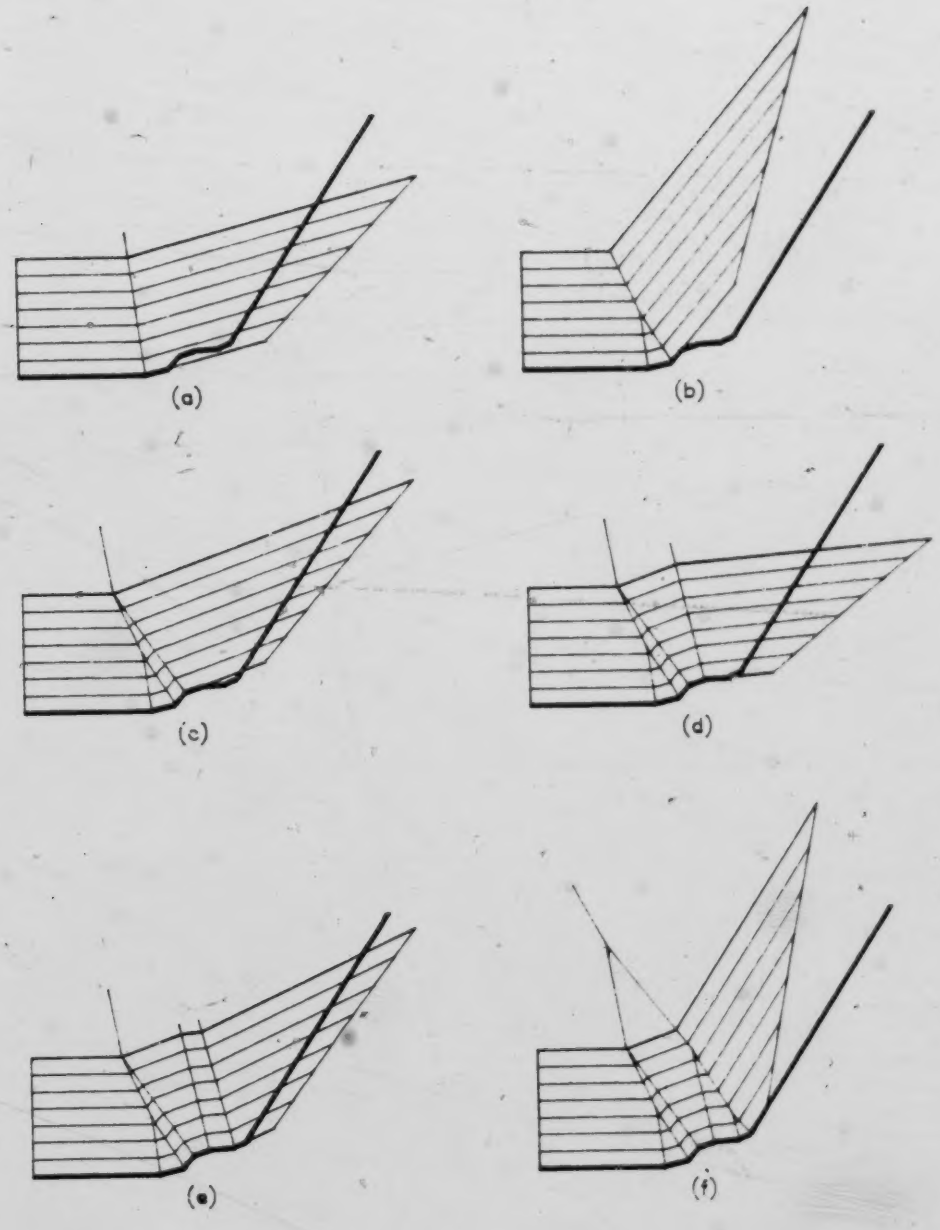


FIGURE 20. Diagrams (a) to (f) show how complicated tree structures can form during the folding of a hanging wall to an irregular fault trace. The same result would occur where there was a linear fault trace but an irregular hanging wall block shape.

Because the current axial trace can intersect previous axial traces during the folding process, an array has been set up to store the nodes of all axial traces formed during one folding sequence. Updating this array with new axial traces and trees is a complicated procedure. The intersection of axial traces results in the creation of new nodes and the destruction of some old ones. At the same time the new and old nodes must be re-organized in a tree structure. The creation, destruction and reorganization can occur many times in one execution of substep (3) if the resultant axial trace at each intersection also intersects with previous trees. This multiple step process can be visualized as the "refraction" of the current axial trace through a network of earlier axial traces. At each intersection the calculation of the new resultant axial trace requires the dip of the strata on the left-hand side of the intersected branch. Thus this value must be stored in the database. The trace along which the hanging wall will be folded is the new right-hand edge of the right-most tree after the "refraction" process. All previous folds to the right of this trace are erased. As the reader can appreciate, a large portion of the program is devoted to creating and modifying the tree networks that define the axial traces.

A pointer system is used to store the trees. In common with other sections of the database, the X and Y coordinates of the tree nodes are stored in paired arrays,

named TREEX and TREEY (Fig. 21). The actual order of the nodes in these arrays is random except for the "root" or topmost point of the tree, which always occupies the first element of the array rows (arrays store trees by row). The other nodes in a tree are related to each other by a system of tags. These tags are stored in a third array, TREET (Fig. 21). The root node has a tag of 0. The first node below the root is tagged with 1. The tags for each branch node below are defined by the rule: the left and right nodes below a fork are 2N and 2N+1, where N equals the fork node's tag. Thus from any node in the tree it is easy to retrieve the coordinates of any of the three connecting nodes by calculating the appropriate tag number. The lower branch tags are described by the above rule and the tag of the node above is the result of integer division by 2 (discarding the remainder) on the present tag.

Since new intersections of axial traces are stored in the empty location at the end of the tree array rows, the order of nodes in the tree becomes semi-random after a number of unpredictable intersections between newly calculated axial traces and the tree. Searches for a given tag are therefore sequential. There are no "end of tree branch" indicators associated with the tags; the program only knows it has run off a branch while searching down the tree if the tag search returns a not found value. As noted earlier the "refraction" process requires that the dip of strata on the left-hand side of each intersection be known.

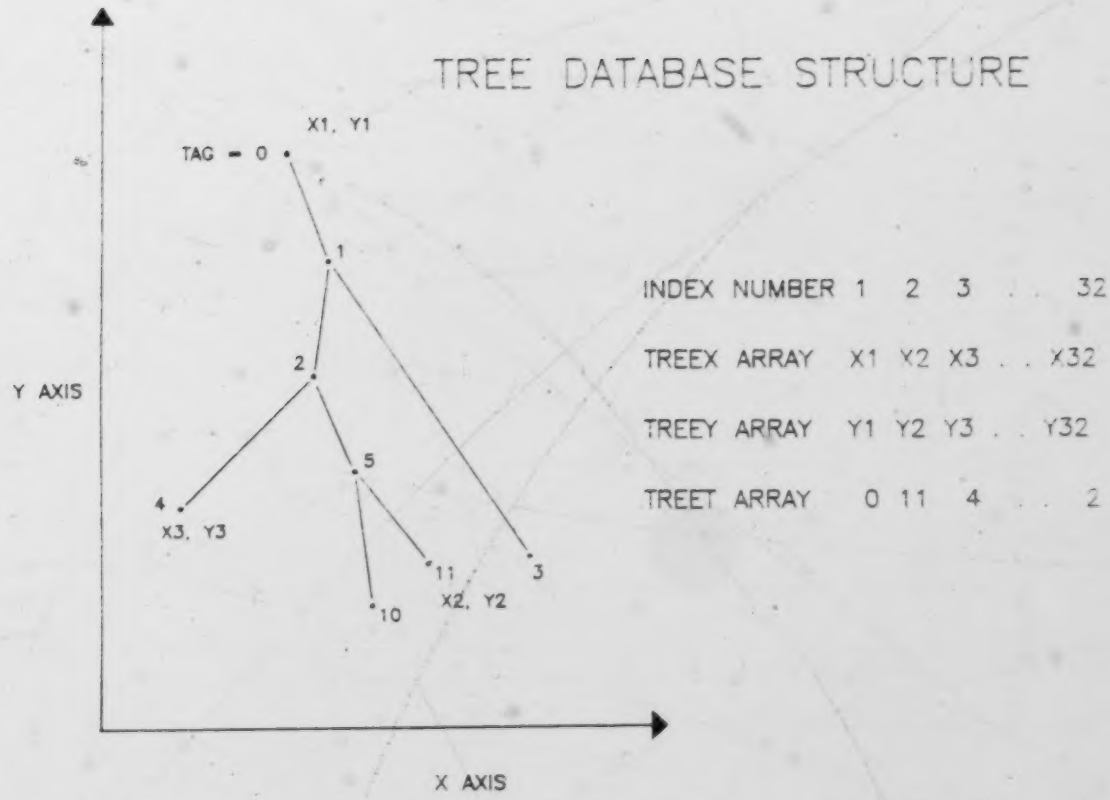


FIGURE 21. The organization of the arrays containing the axial trace tree structures.

Thus it is necessary to include alongside the X, Y, and tag

arrays an array containing the value of the bedding dip on the left-hand side of each branch segment (TRDIP). This value is a real number defining the slope of the bedding to the left of the node at the bottom of the branch. For the purposes of calculating the trace originating at any intersection, the right-hand slope of the strata is, as previously mentioned, the new dip of the hanging wall strata to the right of the basal hinge point.

Under certain conditions the process of coalescing two axial traces can isolate an axial trace previously belonging to a tree (Fig. 22). This is most likely to occur when two synclines in the hanging wall are succeeded along the fault by an anticline. In such cases, the axial traces converge, but the resultant axial trace instead of refracting to the left (Fig. 18) refracts to the right and some nodes in the current tree may disappear. Although in theory only a few branches of the current tree may need to be reconfigured because of the anticlinal axial trace, in practice the tree is recalculated by checking all basal branches for intersections with adjacent branches. If during the reconfiguring process, some of these basal branches fail to coalesce with adjacent branches, the tree dissimilates into smaller trees (Fig. 22).

As a consequence of coalescing traces and dissimilating trees, folding may result in a sequence of construction and destruction of tree networks. In such a situation, it would be advantageous, as happens during the

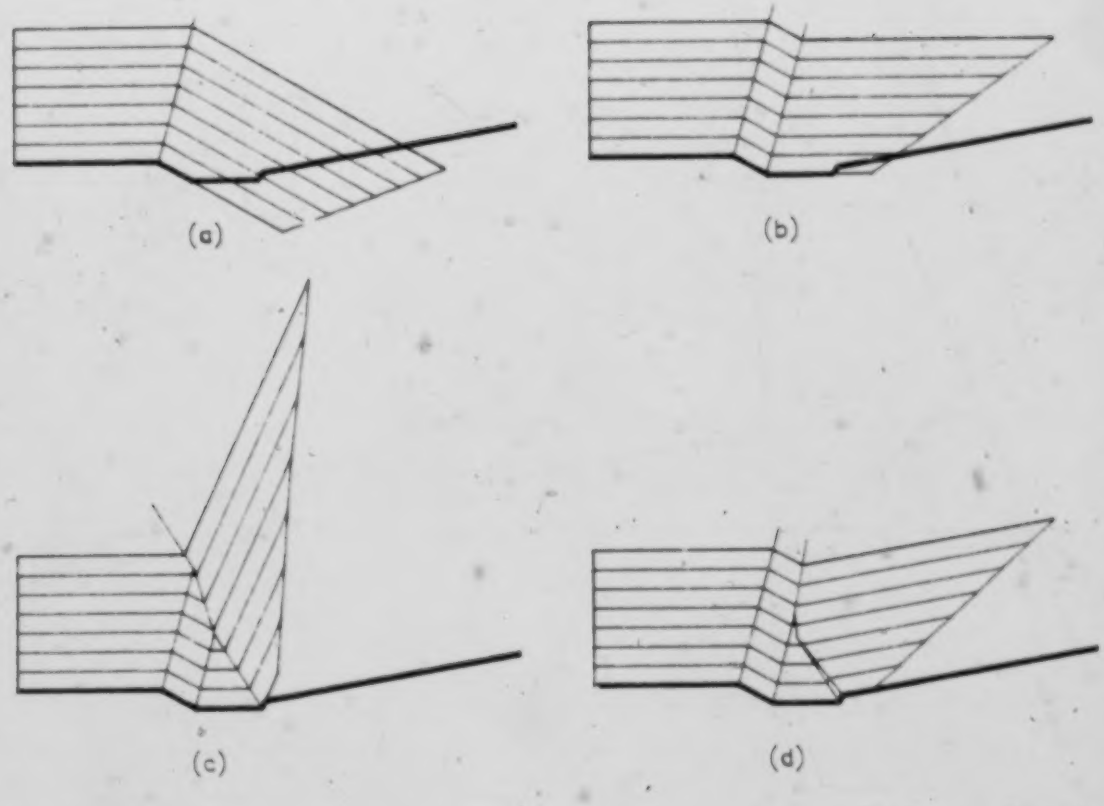


FIGURE 22. The formation of a single axial tree structure and its subsequent dissimilation during a folding sequence.

reconfiguring process discussed above, to find all the axial traces, coalesce them all at once, and bend the contacts through the completed network of trees. Unfortunately, each succeeding axial trace depends on the dip and truncation angle of bedding in the block ahead of the hinge point, which means the program must actually have folded the hanging wall block to the fault up to that point.

Substep (4) Fault Block Bending

The bending substep consists of relocating bedding contact points in the block to the right of the axial trace. In effect the stratigraphic contacts are rotated about their intersection with the axial trace until they match the new dip calculated during the axial trace determination substep. The routine works upwards contact by contact, finding the intersection between the contact and the newly calculated axial trace, then relocating the relevant contact segment nodes along the new dip line. The axial trace may be either a line or a series of non-parallel segments comprising the right-hand edge of the tree farthest to the right.

Because the current axial trace may have erased a portion of a previous axial trace, there may be folds in the stratigraphic contacts which are now invalid. If the old folds are to the right of the new axial trace the

solution to erasing them is simple. The program measures the length of the bedding trace to the right of the new hinge point and uses this length to construct a new straight bedding trace at the appropriate dip. All old hinge points to the right of the current hinge point are removed from the arrays.

Where the invalid folds are to the left of the current axial trace, the situation is more complicated. In such cases the bedding traces must be straightened and then refolded forward from the last tree undisturbed by the erasing of branches. When the refolding is completed to the current axial trace the folding can proceed as above.

There are some subtle effects of simple shear parallel to bedding which require another operation to be included in the folding substep. This operation, executed after folding, reconfigures the perimeter of the block. The operation is necessary because in some instances the effect of shear is to change the shape of the block in such a way as to require extra points to be inserted into the perimeter. The shape changes result from changes in the value of bed-parallel simple shear across bedding planes. It can easily be seen that where such changes occur in the shear there will be corresponding changes in the truncation angle at the right-hand edge of the hanging wall block. The shear-induced changes in the truncation angle must be located and nodes inserted in the perimeter during folding as these changes in the truncation angle will become hinge

points for later folds.

To see how the stratigraphic succession can become divided into bed-parallel zones of different simple shear strain, let us examine the equation for the change in simple shear ( ) across an axial trace:

= 2/TAN

where equals the angle between the axial trace and the bedding trace.

This equation assumes that the left-hand side bedding is "locked" and that all flexural slip takes place on the "open" or right hand side of the fold (Appendix 2). It can easily be demonstrated that, where axial traces coalesce, the two shallower bends below the intersection induce less net change of the value of unit shear affecting the strata, than the single sharper bend above the intersection (Fig. 23). Thus to the right of the point where two axial traces coalesce into one, the simple shear is not homogenous normal to the strata, i.e. the strata have been divided into bed-parallel zones of different simple shear. Of course these zones will exist only as long as the tree node, from which the demarcation line between them originates, exists. Thus the pattern of simple shear affecting the shape of the right-hand end of the hanging wall block must be updated with every reconfiguration of

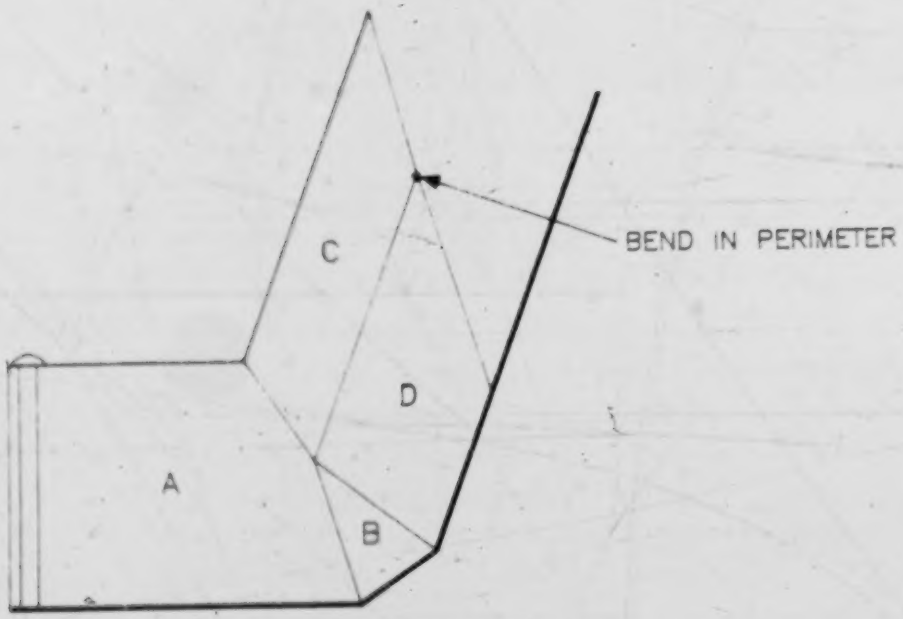


FIGURE 23. The distribution of simple bedding plane shear within a block. Panel A is unsheared, all other panels have different values for the shear angle. The difference in the shear between panels C and D results in a different apparent truncation angle for each panel. Because of this a node must be inserted into the perimeter as indicated.

the tree network.

The fold step, a repeating sequence of four substeps, terminates when the foreland tip of the block being folded lies along the fault trace. Where deformation consists of more than one episode of faulting, two or more blocks have to be moved separately, i.e. the folding routine is repeated in a sequence beginning with redefinition of the active fault.

Fault Redefinition

Where deformation consists of more than one episode of faulting, during all but the first episode, fault-bounded blocks in hanging wall assemblages are displaced separately to simplify the axial trace solutions. Blocks belonging to the assemblage must be moved one by one, beginning with the lowest. They must be moved in this order since the folds in overlying blocks are dependent on the shape of underlying blocks. The lowest block is displaced and folded to the current active fault. All subsequently moved blocks are displaced along and folded to a fault consisting of parts of this fault and older faults separating hanging wall blocks. For this reason, the active fault must be redefined before movement of each subsequent block. Redefinition is accomplished by replacing in the FX and FY arrays the nodes of the last active fault where it is covered by the last block to be moved, with the nodes representing the upper trace of the last moved block, i.e. a folded earlier fault. Though they are moved separately, the blocks do not change position within the assemblage. This is the only simple way to model folding in a hanging wall containing more than one block. The movement of a hanging wall assemblage generally results in each successive active fault becoming progressively more irregular as horses stack on one another.

Order of Block Movement

The order in which blocks move is controlled by their relative positions such that the lowest block is moved first, the highest last. In most cases, a block's position along the current user-defined fault can be used to determine the stacking order, as long as the left end of the base of each block lies along this current fault. If this condition holds, then the block farthest to the right moves first, the block farthest to the left moves (Fig. 24).

If all blocks are not in contact with the current fault (Fig. 25) the program can still simulate the movement of the hanging wall assemblage. This is accomplished by repeating the following sequence: (1) locating the block farthest to the right on the active fault, (2) recording the displacement of this block from the left end of the cross-section, and (3) redefining the active fault as the top of this block plus the portions of the active fault not below this block. These steps are repeated until all blocks in the hanging wall are recorded in an array. The order of movement for the blocks is the order in which they are found, and the displacement for each block is the current displacement plus the distance measured in step (2). Note that this method does not maintain the contact relationship between blocks in the hanging wall during displacement. Since there must be some interblock slip during the

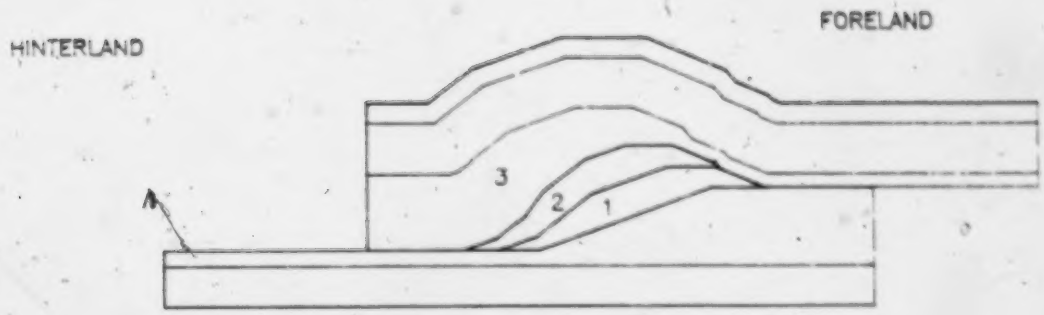


FIGURE 24. The order of block movement in the hanging wall assemblage is 1, 2, and 3.

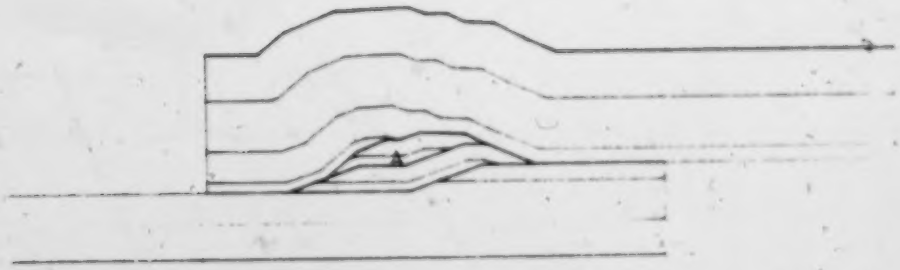


FIGURE 25. A hanging wall block (A) not in contact at any point with the current active fault.

displacement of an actual hanging wall, and since the amount of slip in the model is small, this is acceptable.

Summary

The movement of all blocks belonging to the hanging wall is the last of the three main procedures. On the completion of this step the program can either terminate after drawing the output, or return to input another fault and its displacement. In summary, the program creates, divides and deforms two-dimensional stratified cross sections in such a way that each layer retains its thickness and the area of each is conserved. Despite (1) limitations in the allowed configurations of faults, (2) artificial assumptions on the behavior of hanging wall blocks and (3) a disregard of energy considerations, balanced, geometrically accurate structural cross-sections are created by the program. The application of such a program is a powerful tool in the investigation of thrust belts.

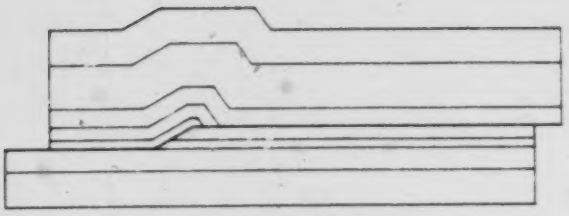
APPLICATIONS

Applications of the computer program described in the previous chapter can be divided into three categories: (1) teaching, (2) cross-section testing, and (3) theory formulation. While the program can accomplish tasks in all three categories, it is not equally adept at each. Although it was designed primarily to perform in the second and third categories, the program can be used for teaching.

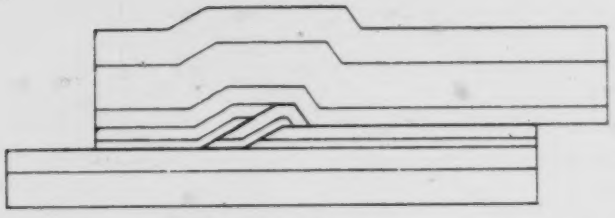
Teaching Functions

The program has shortcomings as far as teaching is concerned. The major shortcoming is the complicated nature of the user-computer interface. Because the method of communication is not user-friendly, a student must devote much of the time learning command sequences rather than analysing output cross-sections. The significant demands placed on the student in finding acceptable configurations are offset, however, by the ability of the program to use these configurations to construct many different geometrically accurate models in a short period of time.

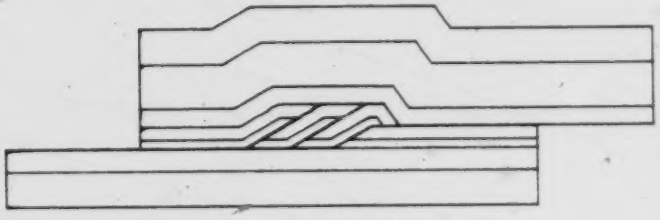
An example of the type of structure which could be created for the purpose of demonstrating structural concepts to students of geology is the duplex (Fig. 26). Display of the output cross-section after each stage of faulting enables the student to understand how a duplex



FAULT STAGE 1



FAULT STAGE 2



FAULT STAGE 3

FIGURE 26. The development of a three stage duplex.

grows. Note that output from the program demonstrates to the student not only the final geometry of the faults, but also graphically illustrates the displacement of the hanging wall at each stage.

To create an ideal duplex, whose roof and floor thrust are parallel and where each ramp makes an angle of 30 degrees with bedding, the length and displacement of each horse must be 2T and 4T respectively, where T is the thickness of the enclosed strata (Boyer and Elliott, 1982). The student must use these relationships to make up an appropriate series of responses to prompts emitted by the program (Appendix 3).

Another example of a useful teaching model is the antiformal stack (Fig. 27). The interactive nature of the program is useful in constructing such features since it allows the student to view the geometry at the end of each stage of deformation before making decisions about the geometry and displacement of the next stage. Building an antiformal stack is more of a trial and error procedure than building a duplex, but generally the displacement must be less than twice than the length of the horses. The student can construct a stack by keeping the responses to computer prompts within this range (Appendix 3).

The antiformal stack model shows more than the geometry of fault bend folds. The bed-parallel bands delineating fields of different simple shear, described in

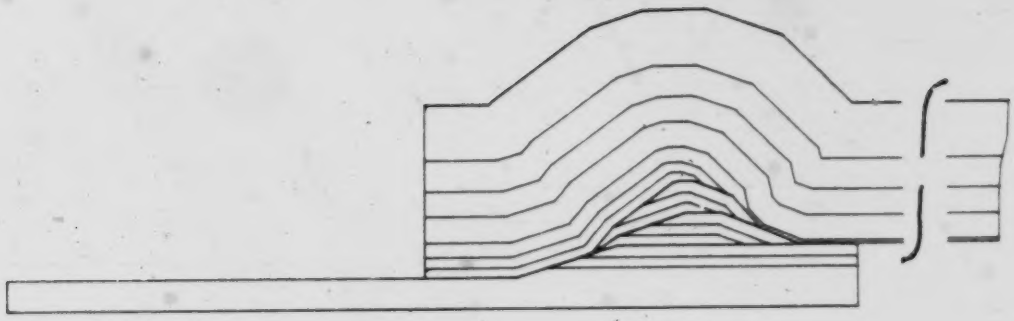


FIGURE 27. An antiformal stack. Note the displacement required to construct the three stage stack.

chapter 3, result in shape changes to the originally straight foreland end of the hanging wall block, the shape changes occurring at changes in the value of simple shear. From this shape the student can gain an understanding of the effect of the bedding plane shear induced by folding ahead of the deformation.

Duplexes and anticlinal stacks are examples of structures that students can model with the program. The primary values of the program as a teaching tool lie in the speed with which models are constructed and the interactive nature of the construction process. Neither of these qualities makes this program unique. THRUST and THRUSTBELT, mentioned in the introduction, are similar programs which present a qualitative result adequate for the purpose of teaching. The program developed for this thesis has its real power in the applications of cross-section testing, and theory formulation, particularly where a quantitative result in the realm of constant-thickness fault bend structuring is desired.

Testing Cross-sections For Balance

The application of cross-section testing uses the program to create models which enable geologic cross-sections constructed using geological, geophysical and drillhole data to be accepted or rejected. The cross sections to be tested must of course include only the types of structures which can be modelled by the program. Cross-sections with such features as out-of-sequence faults, blind faults, buckle folds and intercutaneous wedges cannot be tested.

Duplicating the fault

An interpreted cross-section can be tested by assuming that either the faults or the fault bend folds are correct. In the first approach, the user duplicates the fault geometry in the cross-section. To do this a grid may be superposed on the section and the coordirates of a series of points which reasonably model the fault trace, read off this grid.

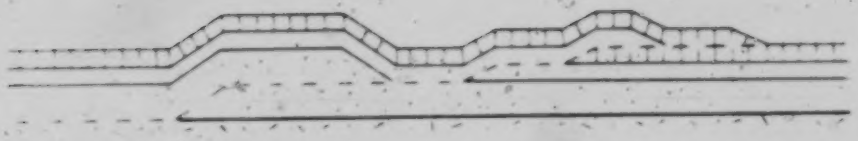
After specifying the geometry of the fault, the user estimates its displacement and contructs a model cross-section. This cross-section is compared with the original section. If the fault bend folds in the model are similar to those in the original cross-section, the latter may be correct. This conclusion can be drawn because the original cross-section has been matched by a model which is perfectly balanced. The match, however, does not guarantee a correct interpretation: depending on the amount of data available to construct the original section, both sections may depart considerably from reality. However, the modelling program can add considerable confidence to an interpretation if the cross-sections match.

If output from the modelling program does not match to a reasonable degree the interpreted cross-section, the user must conclude that errors exist in the interpretation. The computer model cannot discern for the user whether the error lies in the interpreted fault geometry, the fault

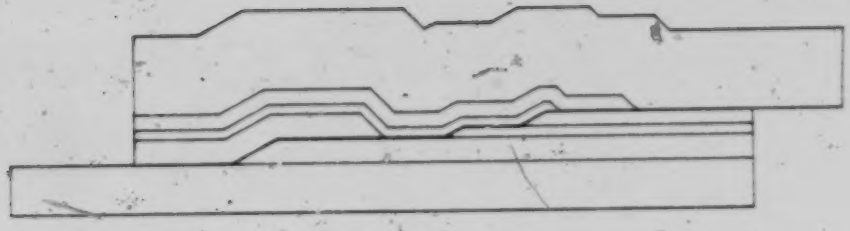
bend folds, the interpreted displacement or all of these, only that such a fault and displacement will not result in the interpreted cross-section under the laws which govern the operation of the program. At this point the user can either reject the interpretation or conclude that the interpretation is balanced, but under conditions different from those assumed by the modelling program. Since the user will likely have decided that the interpreted cross-section abides by the rules governing the program before applying the modelling test, this generally means rejecting the cross-section.

It is easy to test single-fault cross-sections by this method (Fig. 28a). The fault geometry and displacement in such examples are easy to duplicate from the interpretated cross-section, and the computer-created model will clearly show any discrepancies in hanging wall geometry (Fig. 28b). The user decides after comparing the hanging wall of the original with that of the model whether or not the discrepancies are great enough to reject the interpretation.

Modelling cross-sections with two or more faults is much more difficult. In such cases, where an older fault is folded by movement on an underlying younger fault, the original geometry of the older fault is destroyed. A reasonable guess at the older fault's original geometry may be made by noting where it ramps and flats in the stratigraphy and estimating the angles at which the ramps



(a)



(b)

FIGURE 28. Testing a hypothetical cross-section (a, from Gretener, 1972) by constructing a model with identical fault geometry (b). Note the primary difference between the section and model is the unequal forelimb and backlimb angles of the fault bend folds in the model.

propagate. However, this guessing means that the ability to conclusively reject or accept a hypothesis is lost.

There is one application which uses the fault-duplication approach to test a cross-section where the user need not guess at the original trajectories of older faults. This is the testing of palinspastic restorations (Fig. 29). In testing the validity of a restoration, the user duplicates the fault geometry from the restored section (Fig. 28b). Displacements are measured from the original unrestored structural cross-section (Fig. 29a). A model (Fig. 29c) can then be constructed for comparison with the unrestored cross-section. We must bear in mind that this is testing not for balance, since in theory only a balanced cross-section can be restored (Elliott, 1982), but for the correctness of the palinspastic restoration.

Duplicating the fold

The second approach to testing cross-sections, namely, to assume that the fault-bend folds in the original cross-section are correct, does not require knowledge of the original configuration of any fault in the original cross-section. In this approach, the fault-bend folds of an interpreted cross-section are duplicated (if possible) by a computer model (Fig. 30). If the faults in the original (Fig. 30a) and model (Fig. 30b) cross-sections match, the

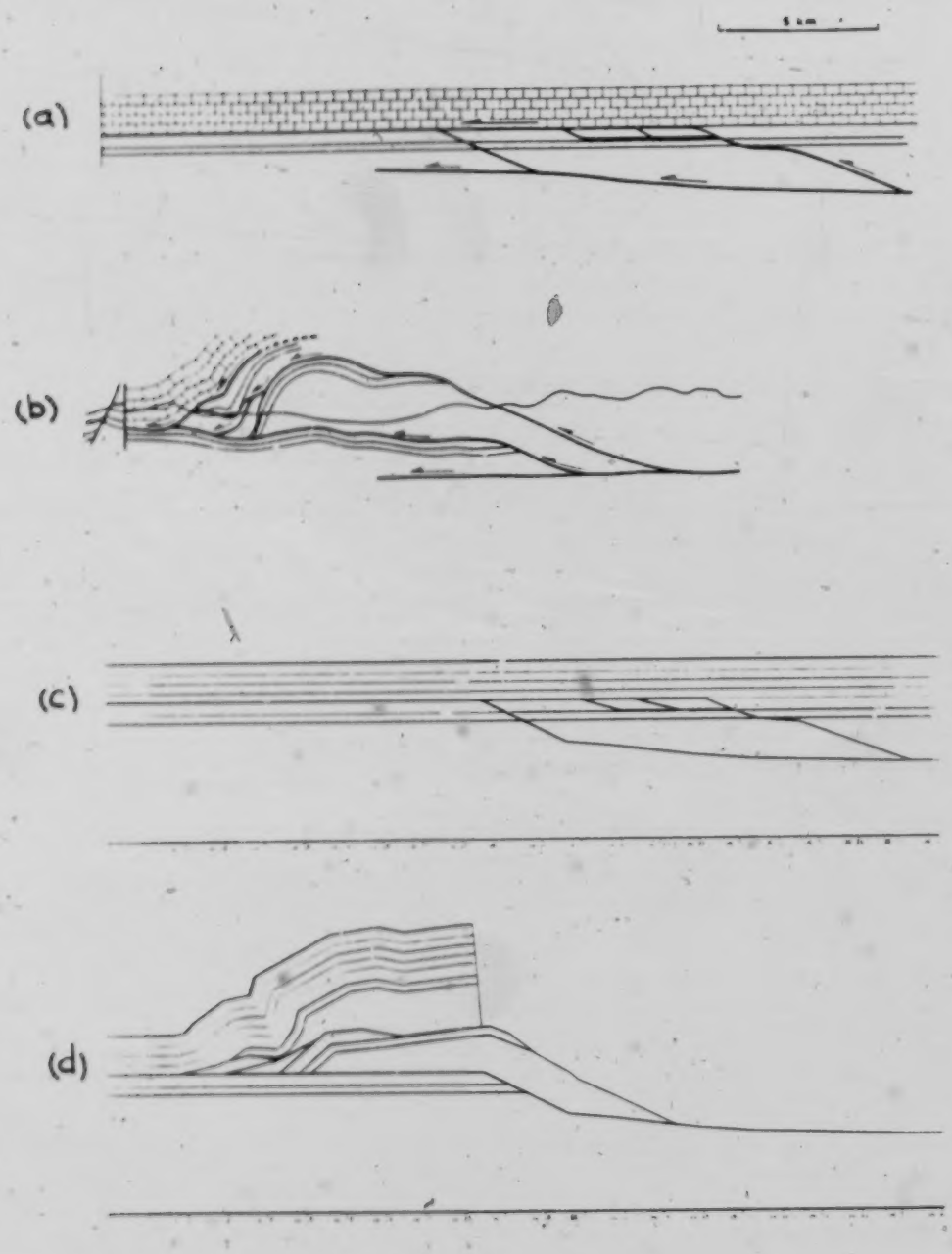
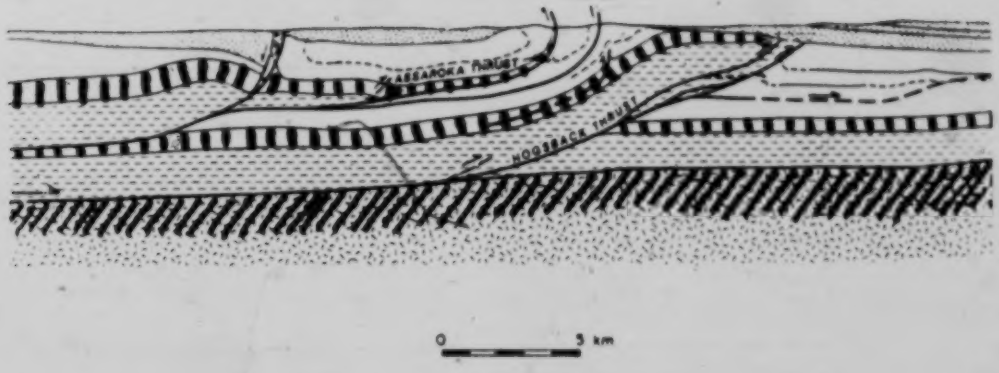
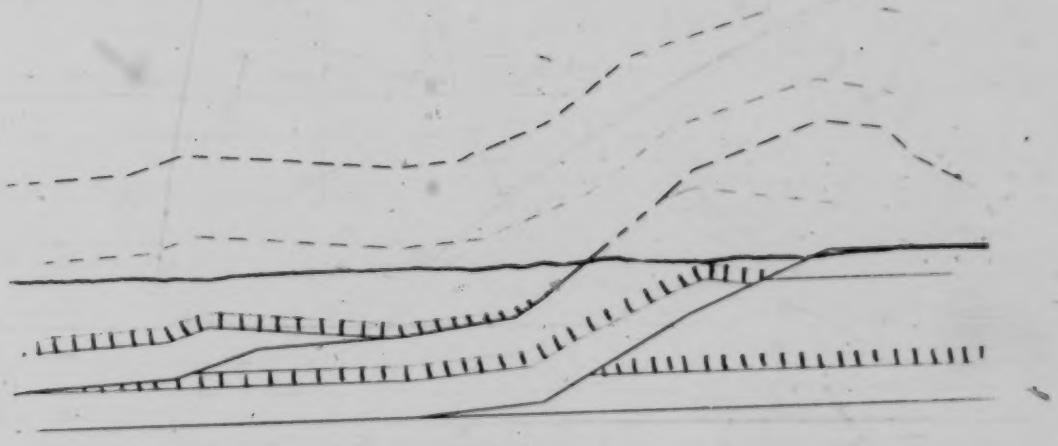


FIGURE 29. Testing the validity of a palinspastic restoration (a, from Williams, 1985) by duplicating the original fault geometry from the restoration, and displacements from the structural cross-section (b), with a model cross-section (c and d).



(a)



(b)

FIGURE 30. Testing an interpretation (a, from Royse, 1975) from a foreland thrust-and-fold belt by contructing (b) a model cross-section which attempts to duplicate the fault bend folds of the interpretation.

former may be correct. If they differ considerably, either the original section is incorrect or the environment being modelled does not abide by the rules under which the modelling program operates. Because a trial-and-error method of testing, modifying and retesting faults and displacements must be used in the attempt to create a duplicate of the folds in the original section, this approach is more difficult to implement than the approach that assumes the fault geometry to be correct. However, in most interpretations the fault-bend folds are the structural elements best defined by the data. Hence the second approach to testing cross-sections should normally be applied, namely, assuming the folds to be correct.

The primary task of the modelling program is to provide assistance in deciding whether or not to accept the hypothesis in question. However, the program can also help formulate alternative hypotheses, even though the model does not indicate the original hypothesis to be correct. The computer modelled cross-section is the source of this help. Using the original data to evaluate the computer model, the computer may be found to have provided a new model or parts of a new model which honors the data as well as the original interpretation. Computer-produced model cross-sections can be used as templates to modify hypotheses in both approaches to cross-section testing.

To be successful, the procedure of cross-section testing requires extensive experience with the computer

program. The user must be able to predict the type of fault which will produce a given fault-bend fold or the types of fault bend folds that will result from a certain fault geometry. Both approaches demand accurate estimation of the displacement of faults. However, no matter how experienced the user, the process of testing cross-sections is based on trial and error. In some cases it may provide definitive evidence on the validity of a interpretation, but the nature of the process means that cross-sections which cannot be duplicated may still be valid.

Finally, it must be remembered that the program can be applied only to cross-sections where the mechanism of deformation is constant-thickness fault-bend folding. Some local structural thickening can be modelled by the use of closely spaced low displacement faults which have their ramps in the stratigraphic unit to be thickened (Fig. 31). This local thickening can be piggy-backed on a large displacement fault, provided no floating blocks are created. The process is somewhat time consuming and, as noted above, demands considerable user experience. It is this type of "trick", however, which greatly extends the applications of the program.

Theory Formulation

The last category of applications, theory formulation, is what this forward modelling program is most

FIGURE 31. Tectonic thickening of a stratigraphic unit by closely spaced low displacement thrust faults.

adept at. Theory formulation consists of using the program as a laboratory tool to help test and conceive new theories. The program may be used to investigate the causes or consequences of particular structural situations. Alternatively the user may experiment with the program to investigate the relationships between faulting, folding and flexural slip.

The experimentation mode is useful to the inexperienced operator. By testing ideas on the relationship of fault geometry and displacement to fold configuration, this class of user gains the knowledge needed for the program to be used to test cross-sections.

The models generated by experimentation need not represent a real situation (Fig. 32). In addition to acquainting the user with constant-thickness fault bend folding, such experimental constructions can often provide new ideas on the origin of thrust and fold belt structures. Such new ideas can then be tested by a more focussed application of the modelling program. The topics for such experiments are limited only by the type of structure the program can model and the imagination of the user.

FIGURE 32. The creation of concentric anticlines by experimental model construction.

Summary

The program has a wide variety of applications, most of which require considerable knowledge of the limitations of the program and the cause-and-effect relationship between faults and fault-bend folds. Because the program is a forward modeller, it is awkward to implement in situations where the user is attempting to duplicate the interpreted final result of a multistage thrusting sequence. This is offset by the power of the program to test hypotheses where the user has control over initial conditions and fault sequencing. Despite the limitations of the program, one has only to consider how long it would take to construct manually the model cross-sections presented in this chapter to appreciate the value of the procedure.

ANCILLARY RESEARCH

Some related areas were investigated during research, namely computer-based modelling of thrust systems. One such area, computer-based palinspastic restoration, deals with many of the same logistical and theoretical difficulties as this thesis and is discussed here. In keeping with the thesis topic the research conducted into this field was limited to restoration in thrust-and-fold belt environments.

Computer-based palinspastic restoration is a major undertaking. This chapter will discuss only some ideas arising from the preliminary investigation conducted concurrently with work on the major topic of the thesis.

Computer-based Palinspastic Restoration

Palinspastic restoration is a subject both parallel and opposite to forward modelling. It is parallel in the sense that it models events identical to those modelled by forward modelling, and opposite because the time sense is reversed. Because of this chronological reversal, palinspastic restoration is more adept at testing cross-sections than forward modelling.

Forward modelling, which begins with hypothetical undisturbed cross-sections, inputs fault shapes and hanging wall displacements that are limited only by the

user's imagination and the ability of rocks to bend by flexural slip. As such it is best suited to testing hypotheses concerning the theory of structural deformation.

Palinspastic restoration, or reverse modelling, begins with a cross-section interpreted from actual data and tests the intepretation for the condition of balance by attempting to undo the faulting and folding events shown in the intepretation. Thus it is designed to test structural hypotheses pertaining to specific cross-sections. Although, as demonstrated in Chapter 4, forward modelling can be used to test such hypotheses, the technique involves repetitive guessing. The technique can show an interpretation to be balanced and therefore possibly correct if the user guesses correctly. Only in a few cases, such as single-fault cross sections, can it conclusively demonstrate a cross-section to be unbalanced and the hypothesis incorrect. Reverse modelling is directed at this shortcoming and can disprove or confirm a constructed section using the premise of balance.

Research conducted by the author into the topic resulted in a computer program which can restore rudimentary structural cross-sections. The algorithm implemented in the program consists of: (1) reading and sorting files containing the digital representation of faults and strata, (2) calculating the area of deformed strata in the hanging wall, (3) calculating the length of the strata in the original undisturbed state using the area

from step 2, and (4) plotting the restored strata at footwall dip. Steps 2 to 4 in the above description are repeated for each separate hanging wall block, working from foreland to hinterland, until all blocks have been restored. Thus the user can observe disparities in bedding length, indicating imbalance at intermediate and final stages of restoration. The computer program in its present state is too simple to apply to any but the most elementry cross-sections, but development work has identified some questions pertinent to computer-based palinspastic restoration procedures.

Such questions can be broken into two broad categories pertaining to: (1) the implementation of structural theory and (2) the mechanics of computer-based restoration. Included in the latter category are questions regarding database structure, the digitizing of cross-sections and suitable output formats. While these questions are pertinent to the thesis topic, this chapter will discuss only the implementation of geologic theory in computer-based palinspastic restoration.

The basic rules of behavior extracted from geologic theory and implemented by the procedure of palinspastic restoration are identical to those on which forward modelling is based. These rules are (1) volume is conserved during tectonic activity, (2) there is little or no mass transfer parallel to strike, and (3) faulting in thrust-and-fold belts progresses chronologically from

hinterland to foreland. A corollary of rules (1) and (2) can be stated as: area is conserved in a vertical plane parallel to the transport direction. The application of these rules to forward modelling has been discussed in Chapter 2. These basic rules are not applied in the same manner to palinspastic restoration.

Consider first the corollary of rules (1) and (2), conservation of area. To the forward-modelling program this corollary means that an interpreted geologic structural cross-section to be tested must be a vertical plane parallel to transport, i.e. perpendicular to strike. Palinspastic restoration, however, can treat oblique sections.

Conservation of area holds for cross-sections not perpendicular to strike as long as the structures are cylindrical in a lateral direction between the ends of the cross-section (Fig. 33). The proof rests on the fact that the area of any geologic unit measured in a vertical plane parallel to transport (perpendicular to strike) maintains a constant ratio to the area of that same unit projected onto a cross-section not perpendicular to strike. This ratio is equal to the secant of the angle between the normals to the two planes of section. This means that for oblique cross-sections spanning cylindrical structural domains, the changes in position and shape of geological units resulting from translation, rotation and strain will not be accompanied by changes in area. In other words, area is

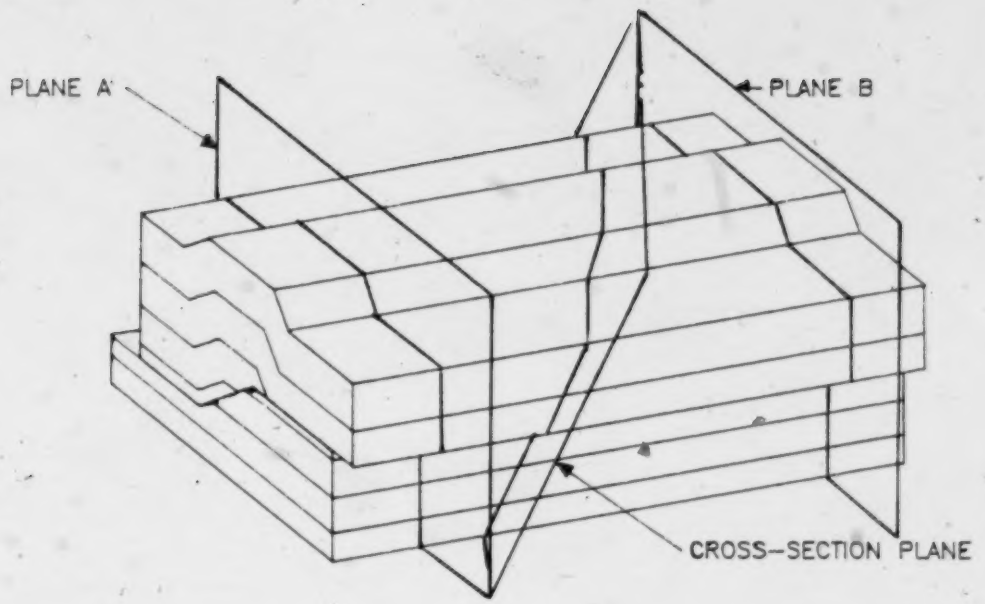


FIGURE 33. The structures as they appear on the cross-section plane can only be palinspastically restored if the structure is cylindrical between planes A and B.

conserved in such cross-sections during tectonic activity despite the fact that there is mass transport into and out of the cross-section.

Because there is, at least in theory, conservation of area in these instances, palinspastic restoration can be attempted. In such cross-sections angles and distances are apparent and not true, and the stratigraphic units do not display their true thicknesses or dips. However, because areas must still balance, the restoration process is a valid test for a correct interpretation oblique to strike. In the case of constant-thickness forward modelling, the thicknesses of units must be preserved, and modelled sections must therefore be confined to sections parallel to the direction of tectonic transport, and perpendicular to strike.

The restoration of cross-sections not perpendicular to strike can only be attempted where the condition of cylindricity over the lateral span of the cross-section holds. In most cases, departures from this condition resulting from lateral variation in fault geometry and displacement mean that cross-sections to be restored can only be slightly oblique.

Another of the geologic rules of behavior which does not have the same implication for palinspastic restoration as for constant-thickness forward modelling is the rule of fault sequencing. According to this rule, the closer of any two faults to the foreland is the younger. Problems arise

when a cross-section being tested by either palinspastic restoration or forward modelling, contains faults which depart from this rule.

In palinspastic restoration, out-of-sequence faults may cause the restoration to appear unbalanced when in fact it is not. For example, in a two-stage deformation sequence, if the first fault-bend is cut by the second fault, the strata cut by the fault have undergone flexural slip and may have been tectonically thickened in the hinge of a fold (Fig. 34a, 34b). On restoration, the flexural slip and tectonic thickening may result in anomalous fault propagation angles and disparities in bed length (Fig. 34d). If the user of the palinspastic routine assumes that the sequence of faulting has been from hinterland to foreland, the structural interpretation will appear to be unbalanced after restoration of the hanging wall block closest to the foreland.

In such a case, the unbalanced cross-section is a consequence of the faulting of strata already shortened by folding, complicated further by the mass transfer associated with non-parallel folding. Such a condition of local structural imbalance indicates that either the original interpretation or the assumption concerning the deformation sequence is wrong. When confronted with such results the user of palinspastic restoration commonly does not have enough information to decide whether assumptions incorporated into the palinspastic technique, or the

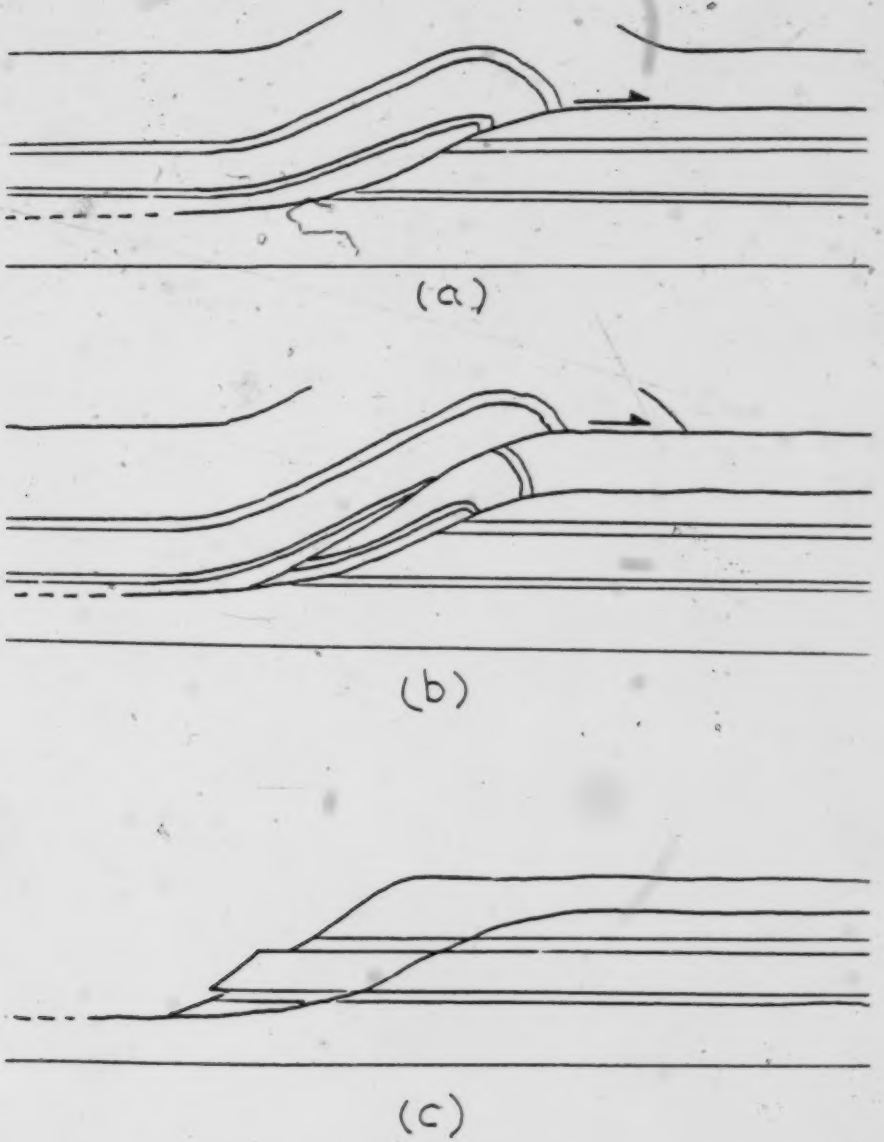


FIGURE 34. How an out-of-sequence fault (a and b) effects the apparent balance condition of the palinspastic restoration (c). The thickened hinge area of the middle stratigraphic unit (a), is cut by an out-of-sequence fault (b). On restoration the lower hanging wall block is resotred first (c) and the additional area of the middle unit within this block results in an anomolous bed length.

structural interpretation, are wrong.

Decisions to accept or reject interpretations at intermediate stages of restoration may be aided by the results of complete restoration of the cross-section. The total restored bed lengths in such completed restorations are independent of the sequencing of deformation within the cross-section and should be the final determining factor on whether an interpretation is possibly correct or not. However, it is important to remember that a cross-section may represent only local geological structure which by itself may not balance on palinspastic restoration. In other words, even if the complete cross-section does not balance, the intepretation may still be a correct one.

The positive side of restoring unbalanced cross-sections is that by observing the restoration stage by stage, the user may alerted as to which portion of the cross-section is incorrect, or to the possibility that rules built into the restoration model do not hold for this cross-section.

The effect of departures from the rule of chronological sequence of faulting has been discussed above. Other rules assumed in restoring cross-sections can also have the effect of creating unbalanced results from correctly interpreted cross-sections.

For example if the restoration procedure assumes that the original stratigraphic thickness is constant within the cross-section, any unit which was locally

thickened or thinned stratigraphically prior to deformation, will show up on the restored section as an anomalously long or short bedding length. The user may interpret this condition as an unbalanced and hence incorrect cross-section when in fact it is not.

Another assumption which may not hold in all cases, but must be used in two-dimensional restoration, is that there is no net lateral transfer of mass into or out of the cross-section to be restored. If such a transfer occurred, the use of area to restore the section will result in apparent imbalance in a correct interpretation.

The prevention of erroneous judgement of departure from the rules of behavior is not easy in most instances, and users must remain aware of the rules incorporated into an automatic routine when judging the results. The effect of such rules must also be considered by the constructor of palinspastic routines. Limits on the complexity of a computer-based routine mean that some generalizations must be made in the application of geologic theory. However, if the generalizations are too broad, the routine will not be able to treat less common structures. It is beneficial to allow the user to modify some of the rules guiding automatic restoration routines, since it both increases the range of applications of the program and reminds users of the implications of departures from the general case.

Summary

Discussion of the application of geologic theory to palinspastic restoration has demonstrated that this tool cannot in all cases provide a conclusive resolution of the correctness of interpreted cross-sections. However, the tool can greatly enhance the assessment of structural interpretations. Proper use of the method demands that the validity of the rules incorporated into the restoration algorithm must be considered before criteria of balance can be used to accept or reject hypotheses.

Palinspastic restoration, at least in the two-dimensional form, is a procedure which can be applied to a wider range of structural regimes than the forward-modelling program of this thesis, which is limited to constant-thickness thrust faulting. In addition, the procedure of restoration is a simpler algorithm to program in the described configuration. While the range of structural environments that be restored by easily programmed routines is wider than forward modelling procedures of equivalent programming complexity, it is limited to testing hypotheses in the form of specific interpretations. In this application, however, it is superior to the forward modelling technique. Ideally, the structural geologist should have both computer-based forward modelling and palinspastic procedures at his disposal.

DISCUSSION AND CONCLUSIONS

Accomplishments

A constant-thickness fault-bend modelling program has been demonstrated to be useful in the investigation of the theory of fault-bend-fold geometry. It has also shown to be valuable in testing the viability of structural cross-sections in thrust-and-fold belts, and for teaching fundamental concepts in fault geometry.

The program's ability to model fault-bend folding where all internal strain is accomplished by simple bedding-plane shear is a substantial improvement over existing forward-modelling routines for thrust faults. At the same time, construction of the program has raised many questions and observations on the distribution of shear within a hanging wall block, and the relative displacement of multiple blocks during deformation.

Possible Improvements to the Program

While it is a useful tool for testing hypotheses in structural geology, the present system limits applications to a narrow range of environments. The program is not capable of modelling environments which include: (1) out of sequence faults, (2) substantial stratigraphic thickening or thinning, (3) intercutaneous wedges, (4) fault

propagation folds, and (5) any mode of strain other than flexural slip.

Some of these features could be modelled by the addition of subroutines to the program. For example, the facility to handle out-of-sequence faults, or faults which propagate from a floor thrust into the hanging wall, would require the addition of only small amounts of code as certain task groups of the program are designed to handle this contingency.

Another relatively straightforward improvement in the program would include the capability to accommodate the modelling of a phenomenon found at the leading edge of deformation in thrust-and-fold belts, the intercutaneous wedge.

An enhancement which would require more code than above would be the ability to model fault-propagation folds. These features are possible in geologic realms where strain is limited to flexural slip (Fig. 35). However, in contrast to the method presented here, it is the foreland end of the hanging wall which experiences zero slip in such faults. Transferring the pin line from the hinterland end to the foreland end of the hanging wall would involve extensive changes to the program.

The program would also require extensive restructuring to enable modelling of either stratigraphic thickness changes or strain not accomplished by flexural slip.

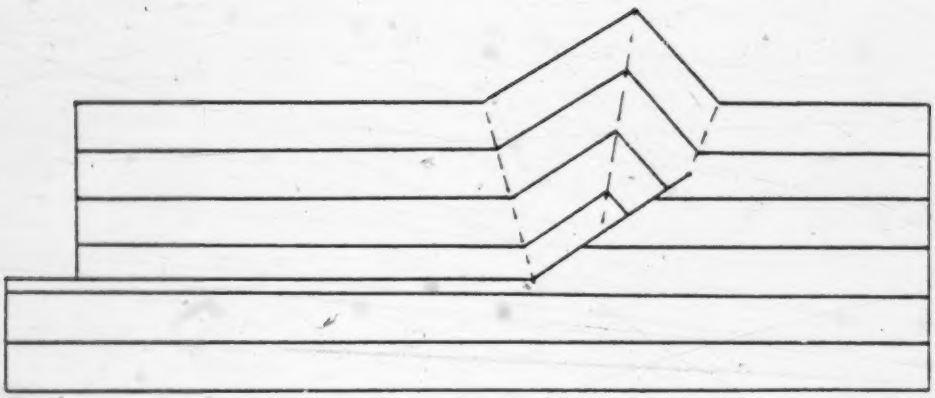


FIGURE 35. A constant-thickness fault propagation fold showing the axial traces.

Future Directions for Forward Modelling

All of these improvements deal with two-dimensional modelling. The next major step in the evolution of forward modelling is the modelling of fault surfaces in three dimensions. Such a procedure would model not only faults with lateral and oblique ramps, but ideally would be able to model the effects of changes in fault displacement along strike. The development of a three-dimensional forward-modelling routine goes beyond simple modifications

of the program presented here, although many of the ideas discussed here can be used as a basis for a such a procedure.

All discussion to this point has dealt with the modelling of geometry. Further evolution of the forward modelling of geologic structures must incorporate energy considerations. How plausible resultant geometry is depends on the user's knowledge of how thrust faults propagate in layered rock sequences. Plausible fault geometry may also be created by computer using the parameters of stress and the mechanical properties of a layered sequence of rock. Such a procedure allows a user to experiment with the thicknesses, specific gravities, and rheological properties of layers in a sequence subjected to a horizontal stress. The vertical stress would be calculated using the gravity of the layers and the effect of topography.

Forward-modelling routines incorporating energy parameters could be used not only to predict fault geometry where the mechanical properties of a rock sequence and stress field are known, but also to test hypotheses on the elevation of the original topography (vertical stress component) at the time of faulting if the horizontal stress field, fault geometry, and sequence properties are known. Integrating the effects of stress and rock mechanics with the geometric results of fault displacement would yield a procedure both complex and powerful. Only with such a routine would it be possible to investigate such questions

as when does a splay fault into the footwall (or hanging wall) occur during thrusting.

Application of energy considerations begins with the modelling of the simplest situations, in the same manner that the program presented herein deals with the simpler two dimensional modelling of thrust fault geometry. It is hoped that despite its simplicity, this program provides not only a tool useful in its present configuration, but a stepping stone of ideas for the evolution of forward and reverse modelling of geologic structures.

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APPENDIX 1.

Derivation of the axial trace equation

Determining the axial trace of a fault bend fold which conserves stratigraphic thickness is accomplished by iterative testing of θ values until α is found to be acceptably close to β (Fig. 1a). This method therefore requires an equation for α and β in terms of θ and the constants H, R, and γ measured by the computer program at each hinge point. As clearly illustrated by Figure a1, α is simply 180 degrees minus θ.

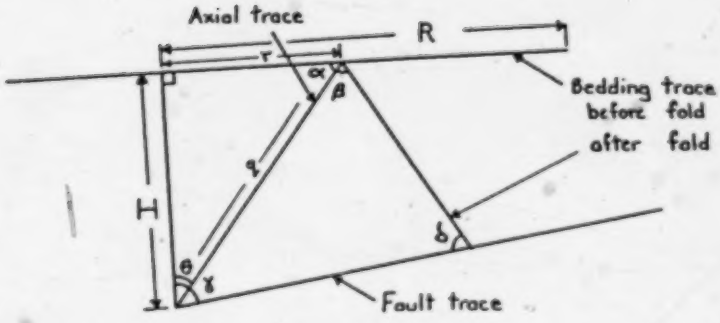

Figure 1a. Elements for determining axial trace of constant thickness fault bend fold.

To solve for β in terms of θ, γ, H, and R consider the triangle formed by the fault, the axial trace to be tested, and the stratigraphic trace folded to touch the fault. From this triangle:

$$(1)\ \beta = 180 - \delta - (\gamma - \theta)$$

The length of the triangle's side formed by the bedding trace (r) is equal to the total length of the trace from the intersection of bedding and the perpendicular to bedding (R), less the portion of the trace to the left of

the axial trace, or:

$$(2)\quad r = R - H*\tan(\theta)$$

The length of the axial trace from the hinge point to the intersection with the bedding trace is another known quantity:

$$(3)\quad q = H/\cos(\theta)$$

Since the angle between the axial trace and the fault is the one known angle of the triangle, using the Law of Sines and the two known triangle side lengths, the angle between the fault and the bedding trace can be calculated:

$$(4)\quad \sin(\delta)/q = \sin(\gamma - \theta)/r$$

Substituting equations (2) and (3) for r and q we can solve for δ:

$$(5)\quad \delta = \text{Arcsin}\ \frac{H*(\sin(\gamma - \theta))}{R\cos(\theta) - H\cos(\theta)}$$

The equation for is obtained by substituting for in equation (1):

$$(6)\quad \beta = 180 - \text{Arcsin}\ \frac{H*(\sin(\gamma - \theta))}{R\cos(\theta) - H\sin(\theta)} + \theta - \gamma$$

Note that where the numerator portion of the Arcsin argument in equation (5) is greater than the denominator there is no solution for D, i.e. the bedding trace right of the axial trace is not long enough to be bent to the fault.

Where the bedding trace must be folded upward to mate with the fault (Fig. 1b) similar use of the Law of Sines applied to a triangle formed by the folded bedding trace, the axial trace, and the fault yields the equation for β for synclines:

$$(7)\quad \beta = \text{Arcsin}\ \frac{H*(\sin(\gamma - \theta))}{R\cos(\theta) + H\sin(\theta)} + \theta + \gamma$$

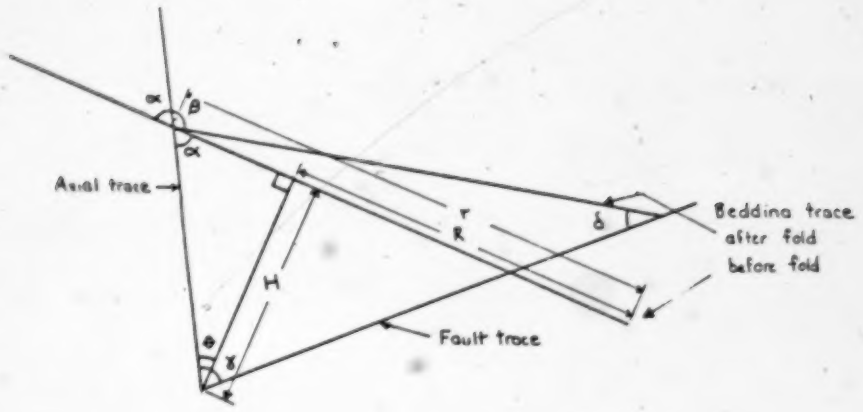

Figure 1b. Elements required to derive the axial trace for a synclinal fold.

APPENDIX 2.

Derivation of the unit shear equation

The derivation of the unit shear, defined as the relative displacement resulting from bed parallel simple shear of parallel strata unit thickness apart, is straight forward for kink folds. In such cases the amount of shear on the hinterland side of the axial trace is assumed to be zero, i.e. the strata behave as if pinned together. To solve for the amount of unit shear induced by folding, consider two bedding traces, unit thickness apart, folded by an axial trace which preserves thickness (Fig. 2a). Construct two right triangles between these bedding traces, which have as a common side the axial trace, and whose bases are equal to the lower bedding trace, and whose upper apices touch the upper bedding trace (Fig. 2a). The amount of shear is the length of the triangle bases combined. Note the bedding perpendicular triangle sides now intersect. Before folding these same perpendiculars were separated along the upper bedding trace by the amount that can now be measured along the triangle base. Since bed length remains constant during simple shear, that is the distance that the point originally corresponding to the right-hand perpendicular is now to the right of the axial trace, or in other words, that is the amount of simple shear.

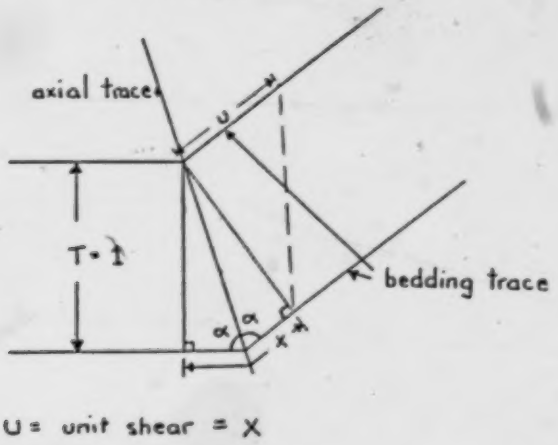

Figure 2a. Elements required for the derivation of the unit shear equation.

Since the amount of unit simple shear is equal to the triangle bases combined then:

(1) $U = 2/\tan(\alpha)$

where T is unit thickness.

APPENDIX 3.

Sample intructions files for TMOD

The following two files show the computer prompt and the keyboard entry sequence during a model construction run. The first file is the command sequence which constructs the first stage of the model shown in Figure 25 and the second demonstrates the sequence required to build the model in Figure 26.

FILE 1

```
D:\>tmod
 ENTER THE NAME OF YOUR INSTRUCTIONS FILE
 OR "KEY" IF YOU WISH TO USE THE KEYBOARD.
? key

 ENTER LENGTH OF THE X-SECTION.
? 120

 ENTER HEIGHT OF THE SECTION.
? 40

 ENTER THE CONTACT SPACING (EIGHT VALUES).
? 8

? 5

? 2

? 3

? 4

? 10

? 10

? 20

 ENTER THE PLOT DEVICE NUMBER.
 1=SCREEN, 2=PRINTER, 3=HP PLOTTER, 4=CALCOMP
? 4

 ENTER THE PLOT FACTOR. (DIAGRAM UNITS/OUTPUT DEVICE UNITS)
? 10.

 ENTER THE NUMBER OF SEGMENTS.
 NUMSEGS MUST BE GREATER THAN 1 AND LESS THAN   32
? 3
```

```
 ENTER THE BEGINNING HEIGHT OF THE FAULT.
? 13.
 ENTER THE X COORDINATES OF THE FAULT SEGMENT ENDS.
? 34.

? 42.67

? 121.

 ENTER THE ANGLE OF EACH SEGMENT FROM THE HORIZONTAL.
 IF YOU WISH TO SPECIFY THE Y VALUE INSTEAD OF THE
 ANGLE, MAKE THE FIRST VALUE EQUAL TO 0.999.
? 0.

? 29.9

? 0.

 DO YOU WANT A PLOT SHOWING THE INCIPIENT FAULT.
? n

 ENTER DISPLACEMENT.
? 10.1

 DO YOU WANT A PLOT OF THE SECTION AT THIS STAGE.
? y

 ENTER THE TITLE OF THE PLOT.
? fault stage 1

 DO YOU WISH ANOTHER FAULT STAGE.
? n

Execution terminated : 0


 FILE 2


D:\>tmod
 ENTER THE NAME OF YOUR INSTRUCTIONS FILE
 OR "KEY" IF YOU WISH TO USE THE KEYBOARD.
? key

 ENTER LENGTH OF THE X-SECTION.
? 167

 ENTER HEIGHT OF THE SECTION.
? 40

 ENTER THE CONTACT SPACING (EIGHT VALUES).
? 8
```

```
? 2

? 3

? 5

? 5

? 6

? 7

? 8

 ENTER THE PLOT DEVICE NUMBER.
 1=SCREEN, 2=PRINTER, 3=HP PLOTTER, 4=CALCOMP
? 4

 ENTER THE PLOT FACTOR. (DIAGRAM UNITS/OUTPUT DEVICE UNITS)
? 10.

 ENTER THE NUMBER OF SEGMENTS.
 NUMSEGS MUST BE GREATER THAN 1 AND LESS THAN   32
? 3

 ENTER THE BEGINNING HEIGHT OF THE FAULT.
? 6.
 ENTER THE X COORDINATES OF THE FAULT SEGMENT ENDS.
? 55.

? 75.

? 168.

 ENTER THE ANGLE OF EACH SEGMENT FROM THE HORIZONTAL.
 IF YOU WISH TO SPECIFY THE Y VALUE INSTEAD OF THE
 ANGLE, MAKE THE FIRST VALUE EQUAL TO 0.999.
? 0.

? 17.3

? 0.

 DO YOU WANT A PLOT SHOWING THE INCIPIENT FAULT.
? n

 ENTER DISPLACEMENT.
? 22.

 DO YOU WANT A PLOT OF THE SECTION AT THIS STAGE.
? n

 DO YOU WISH ANOTHER FAULT STAGE.
? y
```

```
 ENTER THE NUMBER OF SEGMENTS.
 NUMSEGS MUST BE GREATER THAN 1 AND LESS THAN   32
? 3

 ENTER THE BEGINNING HEIGHT OF THE FAULT.
? 6.

 ENTER THE X COORDINATES OF THE FAULT SEGMENT ENDS.
? 76.

? 96.

? 168.

 ENTER THE ANGLE OF EACH SEGMENT FROM THE HORIZONTAL.
 IF YOU WISH TO SPECIFY THE Y VALUE INSTEAD OF THE
 ANGLE, MAKE THE FIRST VALUE EQUAL TO 0.999.
? 0.

? 17.5

? 0.

 DO YOU WANT A PLOT SHOWING THE INCIPIENT FAULT.
? n

 ENTER DISPLACEMENT.
? 20.

 DO YOU WANT A PLOT OF THE SECTION AT THIS STAGE.
? n

 DO YOU WISH ANOTHER FAULT STAGE.
? y

 ENTER THE NUMBER OF SEGMENTS.
 NUMSEGS MUST BE GREATER THAN 1 AND LESS THAN   32
? 3

 ENTER THE BEGINNING HEIGHT OF THE FAULT.
? 6.

ENTER THE X COORDINATES OF THE FAULT SEGMENT ENDS.
? 100.

? 120.

? 168.

 ENTER THE ANGLE OF EACH SEGMENT FROM THE HORIZONTAL.
 IF YOU WISH TO SPECIFY THE Y VALUE INSTEAD OF THE
 ANGLE, MAKE THE FIRST VALUE EQUAL TO 0.999.
? 0.
```